Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy - Background on Concepts, Visions and Measurements

Zeug, Walther; Bezama, Alberto; Thrän, Daniela

UFZ HELMHOLTZ Centre for Environmental Research

UFZ Discussion Papers

Department of Bioenergy

7/2020

Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements

Walther Zeug, Alberto Bezama, Daniela Thrän

August 2020

Publisher:
Helmholtz-Zentrum für Umweltforschung GmbH – UFZ
Permoserstr. 15
04318 Leipzig

ISSN 1436-140X

Discussion Paper

Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements

Walther Zeug [1,*], Alberto Bezama [1], Daniela Thrän [1,2]

[1] Department of Bioenergy, Helmholtz-Centre for Environmental Research (UFZ), 04318 Leipzig, Germany

[2] Bioenergy Systems Department, Deutsches Biomasseforschungszentrum (DBFZ), 04318 Leipzig, Germany

* Correspondence: walther.zeug@ufz.de; Tel.: +49-341-235-4775

Abstract:

Current economic and social systems transgress several ecological planetary boundaries by far but without sufficiently fulfilling human needs and this in a globally unequal way, posing enormous challenges to political strategies and economic structures. To tackle these challenges, under a bioeconomy, a variety of industrial metabolisms, strategies and visions on substituting fossil resources by renewables and hereto associated societal transformations is formulated. Social, ecological and economic (holistic) sustainability, however, is not an intrinsic character of bioeconomy but rather a possible potential which has to be assessed. Life Cycle Assessments and Life Cycle Sustainability Assessments provide promising frameworks and methods for such holistic sustainability assessments, but face major challenges in regard to underlying sustainability concepts and implementation. First, we discuss and analyze the status quo of Life Cycle Sustainability Assessment especially in regard to underlying sustainability and economic concept and identify their strengths, weaknesses and research gaps. Secondly, we characterize the current bioeconomy discourse and propose a transdisciplinary, holistic and integrated framework for Life Cycle Sustainability Assessment. Based on this discussion and the proposed framework, holistic and integrated Life Cycle Sustainability Assessment can provide a transdisciplinary understanding and specific information on the absolute and relative holistic sustainability of provisioning systems to allow efficient and effective governance.

Keywords: bioeconomy; holistic sustainability; sustainability assessment; SDGs; transdisciplinarity; LCA; LCSA; ILCSA; HILCSA

Content

Figures

Tables

List of Abbreviations

BE	Bioeconomy
CE	Circular Economy
DTT	Distance To Target
EW-MFA	Economy-Wide Material and Energy Flow Accounts
ES	Ecosystem Services
E-LCA	Environmental Life Cycle Assessment
HILCSA	Holistic and Integrated Life Cycle Sustainability Assessment
IAMs	Integrated Assessment Models
ILCSA	Integrated Life Cycle Sustainability Assessment
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
PRP	Performance Reference Points
PB	Planetary Boundaries
SES	Social Ecological Systems
S-LCA	Social Life Cycle Assessment
SRN	Societal Relations to Nature
SDGs	Sustainable Development Goals

1. Introduction

The ecological challenges our global societies face are not only climate change, but it is likely that humanity is about to cross several planetary boundaries (PB) - representing the ecological limits of our planet – with increasing strong, intrinsic, bio- and geophysical feedbacks that are difficult to influence by human actions and partly irreversible (Steffen et al., 2018, Rockström et al., 2009, O'Neill et al., 2018). The political and economic impacts on human societies will be massive, sometimes abrupt and undoubtedly disruptive [ibid.]. To curb this developments and to achieve a sustainable stabilized development pathway within PB in the long-term, a coordinated, deliberate and conscious effort by societies is needed to reconsider our relationship with the ecological system (Steffen et al., 2018), for which a radical change - a transformation - in the way we organize our lives is urgently needed (Editorial Nature Sustainability, 2018).

As one way to address these challenges of decoupling and more sustainable resource use more than 50 countries worldwide have now developed bioeconomy (BE) related policy strategies (German Bioeconomy Council, 2018b, Kleinschmit et al., 2017, Meyer, 2017, Bell et al., 2018) to achieve what is in each strategy is understood as sustainable development. Following the definitions of the European BE Stakeholders Manifesto, the German BE Council and the German BE strategy, in this work we understand BE broadly as "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value added products, such as food, feed, bio-based products, services and bioenergy" "within the framework of a sustainable economy" (German Bioeconomy Council, 2018a). However, there is still no unified definition of BE (OECD, 2018, Meyer, 2017). Broadly, (bio-)economies can be understood as provisioning systems mediating the relationship between resource use and social outcomes. The novelty of the concept of a 'new' BE is the objective to achieve higher efficiency by innovative technologies in biomass usage, maximizing the added value of the produced goods (Ingrao et al., 2018) as well as being a main source of sustainable materials for nearly all economic sectors (Future Earth, 2016). Additionally, it can also be about a cross-sectoral networking of provisioning systems in a circular economy (CE) (European Commission, 2018, Bezama et al., 2019). Meanwhile the Sustainable Development Goals (SDGs) are becoming the standard normative sustainability framework also in BE strategies, policies, and action plans (German Bioeconomy Council, 2018b, Gerdes et al., 2018). Taking the chance of linking BE strategies with the SDGs has already broadened the scope of the BE and its sustainability, and stakeholder participation has shown that social, environmental and economic aspects of sustainability are equally important and related (Zeug et al., 2019).

Renewable or bio, however, does not necessarily mean sustainable. Sustainability is not an intrinsic characteristic but rather a promising potential of BE and only if sustainability is a central objective of the economy itself (Chisti, 2010, Pfau et al., 2014, Gawel et al., 2019). Evaluating the ecological, social and economic risks and chances of a developing BE requires scientific and comparable methods of holistic sustainability assessments. In the past, research studies on BE mainly focused upon the technical valorization of biomass and environmental impacts, due to the need for developing an actual technological basis and the material potential for a BE and a possible transformation. However, there is a lack of holistic and systematic approaches to the BE at national and regional levels, and consequently to understand the social, psychological, political and economic barriers to a societal transformation towards sustainable bioeconomies in a transdisciplinary manner (Ingrao et al., 2018, Pfau et al., 2014, Gawel et al., 2019). A measurement and evaluation of so called ecological, economic or social sustainability at different scales is the central motivation of different methodological frameworks of life cycle assessments (LCA) and their combination or integration in life cycle sustainability assessments (LCSA) (Bezama et al., 2017). Especially the latter methods of holistic assessment are still at an early stage and a number of research questions concerning methods, harmonization, data and indicators are open (Zimek et al., 2019, Guinée, 2016a, Ingrao et al., 2018). The most comprehensive review of LCSA approaches available identifies the lack of transparent description and discussion about implicitly underlying concepts of sustainability, and resulting difficulties in the classification of indicators and criteria as major obstacles (Wulf et al., 2019).

Considering this, the goal of this work is twofold: first we discuss and analyze the status quo of LCA and LCSA, especially in regard to their underlying sustainability and economic concepts. Secondly, we characterize the current BE discourse and propose a transdisciplinary, holistic and integrated framework for LCSA in the context of BE. For this research we do not apply specific methods, rather we are building on existing comprehensive reviews, reflect on backgrounds and underlying concepts, discuss approaches going beyond the status quo and argue for a methodological framework addressing some of the identified issues.

2. Life Cycle Assessments in the Context of Bioeconomy

Since it is uncertain if BE has a positive impact on global sustainability, there is a need for comprehensive approaches for measuring and assessing sustainability of the BE as prerequisites for creating effective governance (Dietz et al., 2018). When it comes to policy mixes to address the named decoupling challenges and to implement the SDGs via transformations, the interdependencies of social, economic and ecological systems and possible alternatives are vital (Fedrigo-Fazio et al., 2016). This chapter provides a closer discussion of LCA and LCSA approaches to identify their methodological potentials, but also their partly deep-rooted problematic issues which are obstacles for a further development and application of LCSA.

2.1. Social, Environmental and Economic LCA

Especially LCA became increasingly part of policy documents and legislation as tools for supporting effective and efficient policy and decision making, e.g. the Joint Research Centre (JRC) of the European Union built up a European Platform on LCA for harmonization and more consistent use (JRC, 2019). LCAs as well as LCSAs can be broadly characterized by their scales (global, national or regional value-chains, companies and specific products) and scopes (social, economic and ecological aspects) (Bezama et al., 2017).

In this chapter, we take a look at the different scales: LCAs of specific products, production processes and concrete economic facilities and organizations on the micro-level of assessment methods are particularly important for the assessment of relative decoupling, because thresholds are determined indirectly by processes and resource extraction, rather than by resources themselves (Fedrigo-Fazio et al., 2016). However, the sole evaluation of process chains is not sufficient, as e.g. the reduction of GHG in a specific industry does not mean that national or global emissions would also be reduced significantly, what makes assessments on a macro-level necessary (Budzinski et al., 2017, O'Keeffe et al., 2016). In between, as a relatively new field, LCAs and LCSAs are used for regional assessments of material flows and their effects (Balkau and Bezama, 2019). Regions differ in their social, economic and environmental conditions with corresponding differences in strategy, research and implementation. At a sectoral and regional level analyzes are necessary in order to map regional effects in the social and economic sphere and to make visible real ecological improvements at a meso aggregation level of clusters and networks. Region-specific LCA approaches can support local stakeholders by identifying specific sustainability potential, which can be tapped on site by specific measures in contrast to more general, strategic and nation-wide approaches. Thus, in future, research especially meta- and sector-wide studies of regional effects and interventions are needed (Ingrao et al., 2018). Thereby, also effective policy can be increased by providing specific and generally applicable information and there is a higher chance of stakeholder engagement and acceptance on this meso-level (Fedrigo-Fazio et al., 2016) (Figure 1).

Secondly, and more importantly for this research, let us consider the different scopes. Means to monitor progress in reaching the targets set in BE policies and strategies is lacking in many countries. Not only due to a lack of appropriate methods, but also due to a lack of a clear definition of the BE concept and of concrete and measurable targets and objectives, e.g. different interpretations of sustainability and economy as well as missing clear connection to target systems like the SDGs (Bracco et al., 2018). From our point of view, assessing the BE regarding ecological, social as well as economic sustainability is difficult, since it is not always evident what is actually meant by that. When BE is superficially understood as a potential socioeconomic transition toward holistic sustainability, ending poverty, global partnerships, and education play more vital roles. If, on the other hand, BE is understood only as a substitution of primary resources, the changes in socioeconomic dimensions are insignificant in contrast to environmental effects (Zeug et al., 2019). In most strategies, BE is only monitored by economic values and shares of GDP or their objectives are even non-measurable targets, but the main challenge is how to link complex goals and measurement frameworks (Bracco et al., 2018). Since recently, socioeconomic indicators to monitor the EU's and Germany's BE are in development (Ronzon and M'Barek, 2018, Egenolf and Bringezu, 2019).

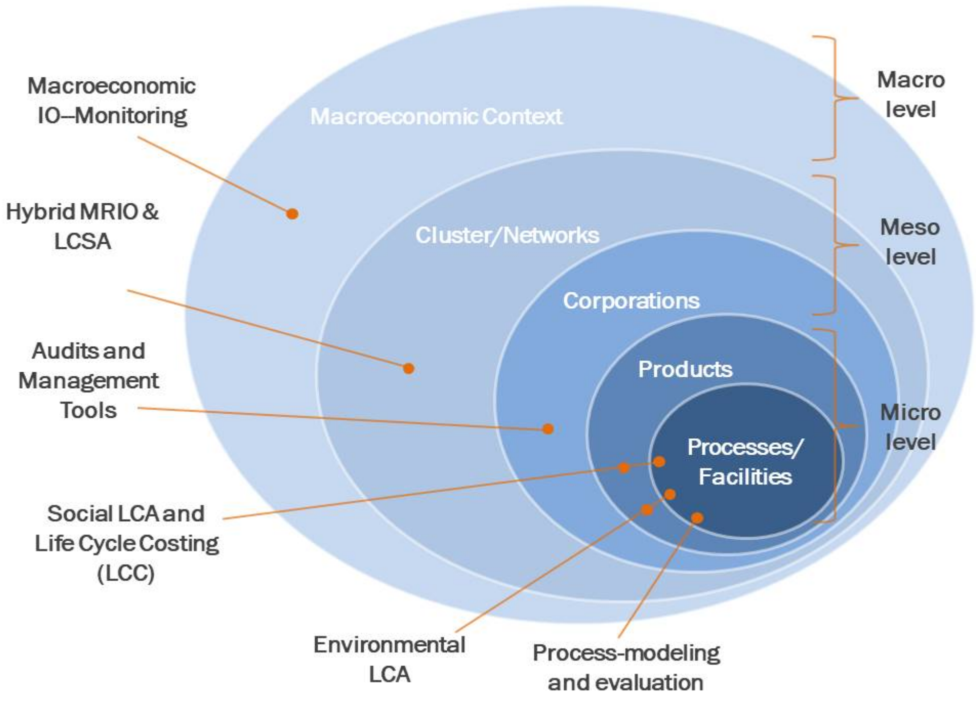

Figure 1, Scales and scopes of BE and appropriate methods of assessment, adapted from (Thrän et al., 2014)

The framework of nearly all LCAs is largely based on environmental LCA (E-LCA) according to DIN EN ISO 14040 and 14044 (Grießhammer et al., 2006, ISO 14040, 2006, ISO 14044, 2006). Main differences are the scopes being assessed: respectively social, environmental or economic sustainability and corresponding indicators (see Table 1). These can be specified by physical quantitative data for E-LCAs, quantitative and qualitative data for Social-LCAs (S-LCA) and quantitative-monetarist data for life-cycle-costing (LCCs) (UNEP, 2009). Recent reviews of LCA methodologies applied to BE showed that 86% of them, the vast majority of all studies, are E-LCA approaches (D'Amato et al., 2020). Apparently, this division of LCA methods is very much based on the three-pillar approach and its characteristics (see section 3.1).

In summary, the existing approaches show significant differences in the main methodological characteristics: goal and scope, functional units, life cycle inventory and model, impact assessment and interpretation. Most important, clear cause and effect chains in S-LCA but also relations between the different assessment methods are missing, especially when it comes to several stakeholders and scales like workers, local communities and national societies (cf. (Jarosch et al., 2020)). Still, LCAs and their indicators should necessarily consider international effects, since first, using local or global indicators depends on the nature of environmental pressures and its causes (global – GHG, local – acidification), and second, a spatial dissociation between places of extraction, production, and consumption distributes the social and economic effects globally (Parrique T., 2019). Mostly, the used indicators in social, environmental and economic assessments tend to be indicators of a weak sustainability approach, when the dimensions of sustainability are seen as interlinked systems and not as embedded and interdependent spheres (Liobikiene et al.).

Table 1, Examples of typical dimensions of sustainability, goals, sub-goals and indicators for the assessment of a BE (cf. (Liobikiene et al.))

Dimensions (Impact categories)	Social sustainability	Ecological sustainability	Economic sustainability
Goals (indices)	Prosperity, health, knowledge	Protection of water, soil and atmosphere	Growth of human-, nature- and real capital
Sub-goals (Indices)	Income and distribution, work safety and stress, qualification, R&D	Climate change, toxicity, resources	Education, demography, resources, investment, profitability
Indicators	Share of employees in the BE sector; labor productivity; public acceptance	The contribution of BE to the reduction of environmental impact; consumption and potential of biomass; Land footprint	Value added and revenue; factor productivity; R&D subsidies and investments; Patents of biotechnologies

2.2. Status Quo of LCSA

LCSAs as the combination or integration of S-LCA, E-LCA and LCC aims to provide a broader and more holistic perspective in sustainability assessments and has been considered by many researchers as essential for a movement towards global sustainable development (OECD, 2018, Zimek et al., 2019, Wagner and Lewandowski, 2018, Balkau and Sonnemann, 2017, Onat et al., 2017, Gao and Bryan, 2017, de Besi and McCormick, 2015). However, LCSA faces the most significant methodological problems. At least there are currently two definitions of LCSA. On the one hand the widely used and highly operationalizing and additive scheme (LCSA=ELCA+LCC+SLCA) first proposed by Klöpffer in 2008 (Klöpffer, 2008). It argues that on the basis of the three-pillar approach, the three methods have to be standardized, harmonized, synchronized (mostly this means an analog brief structure as in DIN EN ISO 14040 and 14044) and then combined whereas extensive qualitative analyses are excluded. On the other hand, there is at least the idea of an integrative approach first proposed by Guinée in 2011, where within a common sustainability concept and methodical framework impact categories from E-LCA, S-LCA and LCC are integrated into a holistic assessment. In this case, LCSA can be understood less as a firm model, but rather more as a flexible framework. Since the sustainability of the BE is a multi-disciplinary and multidimensional field, a series of research papers emphasize and argue that especially integrated approaches are specifically required in this case (Pfau et al., 2014).

At least to date, the authors of this study are not aware of any framework or application of a real integrative and holistic approach of LCSA. Rather, as recent comprehensive reviews (Zimek et al., 2019, D'Amato et al., 2020, Wulf et al., 2019, Fauzi et al., 2019, Costa et al., 2019) and a recent search for LCSAs at Web of Sciences (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018, Mahbub et al., 2019, Vogt Gwerder et al., 2019, Nieder-Heitmann et al., 2019, Opher et al., 2019) show: most LCSA approaches more or less follow the additive scheme and, like LCAs, are explicitly or implicitly based on the three-pillar-approach (Zimek et al., 2019). An explicit theoretically founded framework of holistic sustainability is often missing, which in practical terms leads to different social, economic and ecological dimensions and indicators which are not integrated. But still rather juxtaposed parts and at the end additionally combined by MCDA (Figure 2).

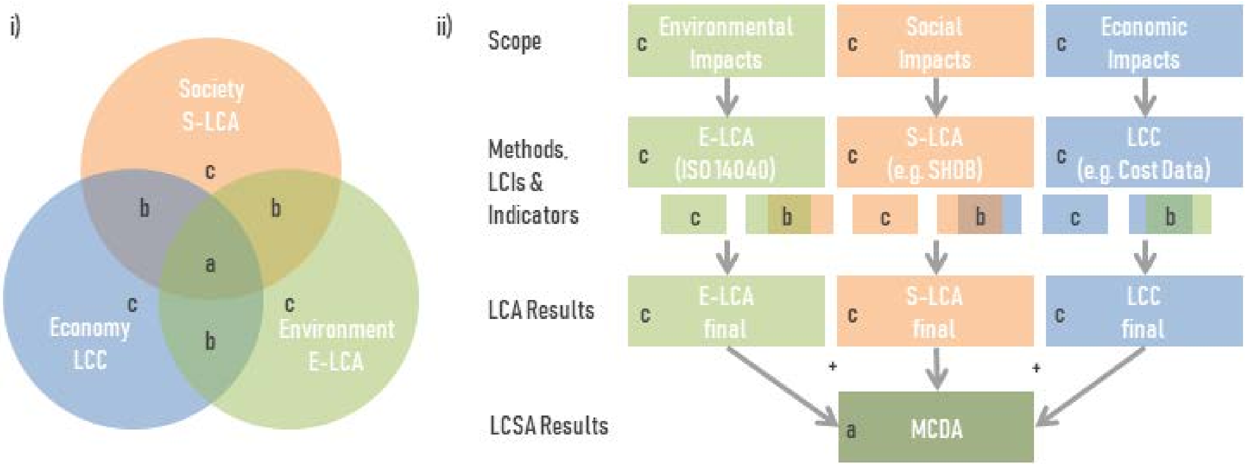

Figure 2, i) Three-pillar-approach of holistic sustainability in LCSA, ii) Widely used additive scheme of LCSA (LCSA=ELCA+LCC+SLCA) by Klöpffer based on i) (c – separate systems (sustainability concepts), methods and indicators (LCSA), b – Intersection between two systems (sustainability concepts), indicators which cannot be clearly assigned to one system (LCSA), a – all dimensions somehow combined (sustainability concepts), additive combination of methods results (LCSA)) (cf. (Suwelack, 2016) Fig. 2.1, (Wagner and Lewandowski, 2018) Fig. 8.22, (Egenolf and Bringezu, 2019) Fig. 1, (Ekener et al., 2018) Fig. 1, (Mahbub et al., 2019) Fig. 1, (Vogt Gwerder et al., 2019) Fig.1))

As an example for this, we consider in a generalized form three LCSA methods (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018)() and one systematic monitoring approach (Egenolf and Bringezu, 2019) with application in the BE: In all cases the conceptual starting point is the three pillar approach of holistic sustainability which is mostly not discussed explicitly, controversially or extensively (Figure 2, i)). Since this domain takes the three parts respectively dimensions of sustainability as the point of departure and considers LCSA as a linear summation and combination of the parts, E-LCA, S-LCA and LCC are carried out more or less independently from each other as separate systems (Figure 2, ii)) (c). Broadly said, scopes, corresponding methods, indicators and LCIs as well as their individual results only have in common that they relate to the same product or functional unit which is to be assessed (cf. (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018)). When assigning the indicators to impact categories, and/or already when indicators are allocated to sustainability dimensions, it becomes apparent that for some indicators or aspects no clear intuitive allocation is possible or useful (e.g. aspects like sustainable final consumption/production, infrastructures, development of rural areas, employment (Egenolf and Bringezu, 2019)). Such aspects mostly describe complex relations between two or more sustainability dimensions and are not even roughly categorizable as solely social, economic or ecological (b). How to deal with such issues is difficult within the three-pillar-approach and separate assessment methods. It not only runs the risk of generating double counting, but also generates unclear cause and effect chains, fuzzy impact categories (e.g. if an indicator is of primarily social, environmental or economic character or which stakeholders are effected) and allocation as well as misleading interpretations. The separate results of S-LCA, E-LCA and LCC are at the end additively combined by MCDA. Relationships between interlinked systems and the SDGs do not play an immanent role.

However, a simple combination of the particulate methods is only possible to a very limited extent (Keller et al., 2015, Wulf et al., 2019, Costa et al., 2019) and also combining the final results with MCDA (Ekener et al., 2018) does not represent a real integration. This is because there is no common methodology and the analysis of complex systems by their subsystems would mean more than just combining their parts (Halog and Manik, 2011). In this regard a series of specific problems results in the operationalization: trade-offs and conflicts of objectives (Guinée, 2016b), double-counting and problems of monetization (Klöpffer, 2008), pareto-effects of high significance within cause-effect relations, contradictions between effects on different scales (Guinée, 2016a), allocation from effects to impact categories (UNEP, 2011), functional units (Costa et al., 2019), exogenous and endogenous weightings in accounting (Traverso et al., 2012), rating, normative goal systems and many more. For instance, the decoupling debate has shown that improving the ecological performance of products only has a limited effect on global environmental challenges, and pareto effects come to bear which makes a relatively small number of causes responsible for a major portion of the effects, resulting in a need for hot spot analyzes (Halog and Manik, 2011). Furthermore, such process-based approaches with a high technical detail, but few general preliminary considerations and conclusions, remain very specific and have a limited significance for systematic analysis of BE regions in a broader context.

Beyond this, there is another approach pursued by ifeu (Institut für Energie- und Umweltforschung Heidelberg), which represents a first but little-noticed development towards integrated LCSA (ILCSA) (Onat et al., 2017, Zimek et al., 2019). Besides integrating other topics, e.g. local environmental effects, a barrier analysis and feedstock availability, there is an integration of S-LCA, E-LCA and LCC by a common LCI with qualitative and quantitative indicators (cf. Figure 4, ii)) as well as an integrated unit process ((Keller et al., 2015) Fig. 2), which we will build on later. But in this method no result integration by aggregation and weighting is conducted, rather benchmark procedures for every indicator. Furthermore, there is no integrated or holistic concept of sustainability and its relations or a connection to SDGs (which did not exist at the time) and stakeholders (Wulf et al., 2019, Keller et al., 2015).

In a nutshell, most of the problems and limitations of the previous presented additive and partly integrated LCSAs can be traced back to deficits in the underlying sustainability concepts, resulting in conceptual, methodological and analytical flaws (Wulf et al., 2019). Thus, the lack of understanding the mutual dependencies and complex interactions among the sustainability indicators, a reductionist approach and myopic view by looking at results of E-LCA, S-LCA, and LCC separately were identified as the major shortcoming of existing LCSA frameworks (Onat et al., 2017, Zimek et al., 2019, Wulf et al., 2019). Generally speaking, a well-founded social, ecological or economic sustainability theory in LCSA is missing. A framework of a holistic sustainability concept based on the SDGs can be regarded as the major hurdle of an integration of the LCA methods and their operationalization in LCSA. In the following chapter we therefore take a look at established concepts of sustainability to gain a better understanding of the implicit backgrounds of LCSA, its deficits and possible alternatives.

3. Background on Sustainability and Economic Concepts and Frameworks

Sustainability and SD have mostly become a collective global value, but remain a challenge for all stakeholders like policymakers, the scientific community, NGOs, business and civil society as the definition of sustainability as a societal transformation and the regional strategies that actually foster it are still ambiguous and continuously debated (Jordan, 2008, Dresner, 2002, Ramcilovic-Suominen and Pülzl, 2018, Editorial Nature Sustainability, 2018, Future Earth, 2016). Terms and concepts of a transformations towards sustainability remain fuzzy and there is much ambiguity and disagreement about the meaning and function of these concepts (Görg et al., 2017). Nonetheless, such transformation will most likely have to innovatively address normative and socioeconomic barriers, like global political patterns of regulation and production and consumption patterns, as well as the technological and ecological challenges (Ingrao et al., 2018). The understanding of sustainability gets even more controversial when it comes to the holistic extension by social and economic dimensions (UNEP, 2011, Elkington, 1998) as well as their relations and contradictions, which remain a fundamental challenge in theoretical and practical terms as we have shown for LCSA (Liu et al., 2015, Gao and Bryan, 2017). Because on the one hand there are neither theoretically in the academic discourse established nor successfully applied integrative concepts of holistic sustainability, and on the other hand practically no country performs well on both the biophysical and social indicators: the more social thresholds countries achieve, the more biophysical boundaries they transgress, and vice versa (O'Neill et al., 2018). Previous research and models building on the "safe and just space"-framework and Doughnut Economics (O'Neill et al., 2019) show that in fact many wealthy nations achieve most of the social thresholds, but at a level of resource use that two to six times beyond the per capita biophysical boundaries (e.g. Germany achieves 11 out of 11 social thresholds but still transgresses 5 out of 7 PBs) (O'Neill et al., 2018). For example, Germanys' environmental footprint is 3.3 times higher than its biocapacity (variable regional and global ecosystems capacity to produce biological resources and to absorb emissions and waste) (GFN, 2019, Network, 2019, Schaefer et al., 2006, Bringezu et al., 2020). At the moment well-being and prosperity seem to be immanently coupled to CO_2 emissions and a high material footprint, but least tightly coupled to the intensity of human use of terrestrial ecosystems due to increases of livestock productivity (O'Neill et al., 2018, Haberl et al., 2012). Nonetheless, especially some social indicators as secondary education, sanitation, access to energy, income and nutrition, which are most important for developing countries, are still most tightly coupled to economic growth and (fossil) resource use (O'Neill et al., 2018).

3.1. Sustainability and Economic Concepts

Although, the terms SD and sustainability are mostly used synonymously today, they actually do not mean the same thing. SD is as a process-oriented approach by means of which sustainability is intended to be achieved. It is based on a dualist anthropocentric view that humankind has a special and almost detached relationship with nature and is only interested in the instrumental or utilitarian value attached to an ecosystem (shallow ecology). Resources should be conserved to be available for future generations and nature should be cared about only to the extent that it is in human interests (Hector et al., 2014). SD is a discursive frame interlinking environmental concerns with human needs by introducing a way to reconcile economic growth with environmental and social concerns on a global scale (Ramcilovic-Suominen and Pülzl, 2018, Meadowcroft, 2007). On the other hand, (strong) sustainability strives for some form of dynamic equilibrium in which the needs of humankind and the needs of nature are both satisfied. In a broader notion of environmental-preservationist this means that the natural world ought to be preserved and must not be allowed to deteriorate, disappear or be dominated by humans (deep ecology) (see Table 2). Here humanity is an integral part of nature, not separate from it and nature has an intrinsic value independent from human or economic interest (Mebratu, 1998, Hector et al., 2014). This polarized constellation of anthropocentric (weak sustainability, shallow ecology, SD) and ecocentric (strong sustainability, deep ecology) views is an epistemological trap: a discussion gets stuck as positions are permanently irreconcilable and based on different self-evident axioms (Hector et al., 2014). This shapes (bio-)economy discourses, practices and assessments:

On the one hand neoclassical environmental economics correspond to weak sustainability because they possess a clearly anthropocentric concept of SD, characterized by benefit and profit maximization. It is assumed that natural capital can be substituted with artificial capital, environment is frequently undervalued, tends to be overused and if the environment only were given its 'proper value' in economic decision-making terms, it would also be protected much more highly (Hector et al., 2014, Mebratu, 1998, Redclift and Benton, 1994). But even within neoclassical models only this constant substitutability of capital stocks and the timely availability of backstop technologies as the BE allow the assumption of non-existent growth limits, without depleting non-renewable and overuse renewable resources (Smulders, 1995). Thus, unlimited economic growth is only possible if enough human capital is allocated in R&D to sufficiently increase the efficiency of resource consumption (Barbier, 1999, Victor et al., 1994, Verdier, 1995, Michel and Rotillon, 1995). When SD is intermeshed with neoclassical economics and in this sense transferred to sustainability assessments like LCSA, we have to be aware of these aspects and of its shortcomings: besides it tends to overlook or deliberately rejects the interests of non-human species, it tends to be mechanistic and reductionist, and based on a positivist view of the ecological system where humankind is regarded as being almost detached from it (Hector et al., 2014). Resulting in a dualism of humankind and nature with a clear hierarchical order that humankind rules over nature (Görg, 2004). Then SD and also LCAs not only tend to treat environmental problems without tackling the underlying causes and assumptions that underlie our current political and economic thinking (Mebratu, 1998), but also see social, environmental as economic aspects and sustainability as rather detached from each other resulting in non-integrative and additive LCSA approaches. Additionally, most LCA based approaches clearly represent an explicit or implicit positivism: reality is seen as independent, objective, empirical and measurable; there are general laws between variables representable by mathematics; methods are model simulations, manipulation of variables and quantitative data; and governance or policymakers 'outside' the system have to pull 'levers' to steer developments.

Table 2, Contents of popular sustainability concepts (Hector et al., 2014, Ramcilovic-Suominen and Pülzl, 2018, Hopwood et al., 2005, Mebratu, 1998)

Keywords	Shallow Ecology Weak sustainability Prudentially-conservationist Anthropocentric Sustainable development	Deep Ecology Strong sustainability Environmental-preservationist Ecocentric Sustainability
Content	Humanity with specific relation towards nature, instrumental value of ecosystems, positivist view, mechanistic systematization, substitutability of capitals, objective: economic sustainable development	Humanity as integral part of nature, intrinsic value of ecosystems, monist and morally egalitarian view, preservation of nature and non-substitutability, objective: sustainable equilibrium

On the other hand, as a result of this criticism and shortcomings, in the 1980s ecological economy developed as an interdisciplinary and more qualitative concept tending towards strong sustainability (Georgescu-Roegen, 1971). In this time and context of ecological economics the term 'bioeconomics' occurred for the first time, but had a completely other meaning than the current term of BE (Birner, 2018) and key messages of both are: the earth is seen as a closed system in which the economy is a subsystem and, therefore, there are limits to resource extraction; a sustainable society system with a high quality of life of all inhabitants within the natural limits is sought; complex systems are of great uncertainties and require a preventative approach; a fair distribution and an efficient allocation are necessary (Costanza et al., 1997, Hauff and Jörg, 2013). In terms of sustainability assessment and LCSA of BE, a consequence is to consider PB as absolute limits of resource extraction. In contrast to pursuing individual gain, benefit and profit maximization, the ecological economy is strengthening the importance of ecological systems for the safeguarding or improvement of human living conditions. In other words, it is about the welfare of the whole society (Hauff and Jörg, 2013). Again in LCSA, this means to switch from GDP and revenues as a form of economic sustainability to a more diverse and direct set of economic indicators like the SDGs. In particular, the assumption of a substitutability of natural and artificial capital is called into question, since human capital is needed to make efficient use of natural capital, and natural capital is needed to generate anthropogenic capital (Hector et al., 2014, Hauff and Jörg, 2013). Capitals are indeed substitutable, but any number of workers and machines or an increase in productivity cannot completely replace the starting materials necessary for production. A necessary increase in productivity can be achieved through three approaches relevant for the BE and their restrictions: increasing flow of natural resources per unit of natural capital, limited by biological growth rates; increasing product output per unit of resource input, limited by mass conservation; increasing efficiency of use of conversion of raw materials into products, limited by technology (Costanza et al., 1997). Models based on the I = P A T function (I – Impacts, P – Population, A – Affluence/ per capita consumption, T – Technologies/economic intensity of resources or pollution) show that growth in GDP ultimately cannot plausibly be decoupled from growth in material and energy use, therefore, GDP and material growth cannot be sustained infinitely in this very economic system (Ward et al., 2016, Common and Stagl, 2005).

The techno-political option space of the BE (Hausknost et al., 2017) shows strong connections to the presented sustainability and economy concepts: "Sustainable Capital" corresponds to the neoclassical perspective and weak sustainability; "Eco-Growth" corresponds to the ecological economics perspective and weak sustainability; "Eco-Retreat" is more a ethical vision of deep ecology, strong sustainability and ecological economics; "Planned Transition" is based on ecological economics but neither corresponds clearly to weak nor strong sustainability.

3.2. Sustainability Frameworks Behind Sustainability Assessments

Since the Brundtland Commission Report in 1987 SD is defined as meeting the needs of the present without compromising the ability of meeting needs in the future (Brundtland et al., 1987). Economic growth to reduce poverty was the specific sense of a solution conferred to, and, in doing so, to create the wealth, technology and commitment necessary to reduce ecological damage. Meanwhile, the so-called three pillar approach (people, planet and prosperity) of the World Summit on SD in 2002 has prevailed and is essential to the present understandings of sustainability (Elkington, 1998, UNEP, 2011, Hector et al., 2014). However, thereby suggested are kinds of several more or less differentiated entities constituting sustainability in a complementary and constructive way (Meadowcroft, 2007). The most established resulting model (see Figure 3) from the three pillar approach is the reductionist model of interlinked systems (Holmberg et al., 1992) as the dominant model which is still mainly used (cf. (Rockström and Sukhdev, 2016)), especially in LCSA (Zimek et al., 2019). And there is a rather less-established model of integrated systems more according to ecological economics (Mebratu, 1996). Presumably rather less-established, since its theoretical conception is less intuitive and requires a well-founded theory as well as its practical implications are far stronger (see section 5).

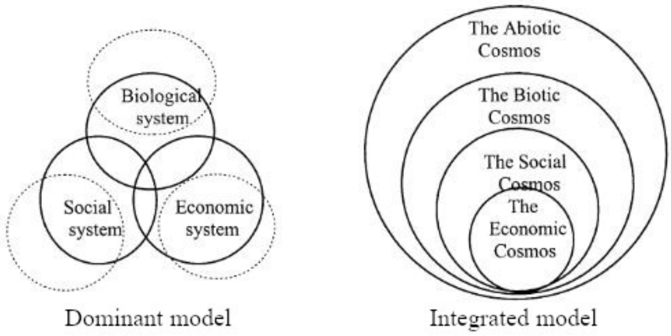

Figure 3, Schemes of sustainability concepts (Mebratu, 1998, Fig. 1)

The established dominant model lead into inflexible and polarized oppositions due to its reductionist epistemological foundations in terms of normatively weak vs. strong and hierarchically of ecological vs. social vs. economic (Redclift and Benton, 1994, Trzyna et al., 1995). Thus, in the ongoing discussion of the last years, a broad spectrum of blended approaches emerged, mainly on the background of complex interactions, spillover effects and increasing importance of transdisciplinarity (Liu et al., 2015). Lately, the lack of a holistic and systematic understanding of social and ecological systems (SES) of the simplified three-pillar-approach was increasingly discussed, even if the term holistic is used inflationary (de Schutter et al., 2019, Purvis et al., 2019). Most important, however, in BE and particularly in LCSA the dominant idea is still to sum up the parts or dimensions of sustainability than to understand their relations: a strong holistic domain has the tendency to take the whole as the conceptual point of departure and take the parts as an add-on, whereas a strong reductionist domain takes the parts as the point of departure and considers the whole as a linear summation. Both approaches proclaim that they apply holistic thinking; however, they are missing the most important element of holistic thinking, i.e. the interactions and relations between the parts in the whole. (Mebratu, 1998)

In a nutshell, a closer look at different economic concepts and sustainability concepts makes clearer why there has been such a mainly technological focus on BE and in most sustainability assessments: in all economic concepts innovations and backstop technologies like the ones strived for by the BE play a decisive role, in neoclassical economics for maintaining growth and the further accumulation of more natural capital. Following ecological economics for our LCSA we assume that a further increase in GDP levels is not considered societal appropriate, since quantitative growth no longer directly improves quality of life and the output of the present level of production in these societies should rather be different and more just distributed (O'Neill et al., 2018, Jackson, 2017, Williams, 2010). If the purpose of the economy is societal wellbeing and to satisfy social needs, GDP is a poor proxy for this, a misleading long-term goal, and should be replaced by more comprehensive goals and indicators like the SDGs (Costanza et al., 2014, Kubiszewski et al., 2013, Ward et al., 2016).

For our work in general, sustainability means finding ways to organize a system where society and nature are mutually connected in a reasonable manner, and therefore a better understanding of the inherent complexity of such a system has to be gained so that we can reconsider our actions and ensure that a system will last (Editorial Nature Sustainability, 2018). In terms of considering the underlying societal and economic principles as well as accepting PB and a limited substitutability of capital, this tends towards strong sustainability. Still, when it comes to sustainability, SD and BE, related key questions arise (Ramcilovic-Suominen and Pülzl, 2018): What are the relations between humans and nature (Hopwood et al., 2005)? In the debate on sustainability and SD the relations of nature, economy and society, especially when it comes to the implications on evaluation, assessment (LCSA) and implementation, receive little attention. And too often the economic, social, political, and cultural crisis is not seen as the cause of our environmental crisis (Mebratu, 1998). And how these relations should be structured normatively (Rametsteiner et al., 2011)? Only data-driven approaches are very limited due to frequently appropriate measures are insufficient, not available or of low quality and moreover they are criticized for lacking theoretical foundations (Spaiser et al., 2017). New concepts of a sustainability science cross-system and transdisciplinary analysis answering these questions should aim at understanding interactions between nature and society, multiple facets of sustainability problems on scales from local to global, which calls for the knowledge input of different disciplinary fields (Zamagni, 2012, Zamagni et al., 2013, Anand, 2016) (cf. (Kates et al., 2001)). Positivism is only one science perspective and IAMs, and LCSAs as IAMs, should be based on a plurality of approaches (Geels et al., 2016).There is a growing consensus about the need for a new way of scientific and sustainability thinking beyond traditional dualisms (subject/object, mind/matter, nature/society, and so on) and mechanistic model, which includes natural sciences, political economy, systems theory, critical theory and cultural theory to understand system complexity like in the societal relations to nature (see section 5) (Mebratu, 1998, Görg et al., 2017).

We have shown in this chapter how basic concepts of weak sustainability, neoclassical and environmental economics as well as the three-pillar-approach implicitly define most of the perceptions of LCSA and respective shortcomings. However, there are alternatives like the integrated model of sustainability setting the basis for our LCSA framework. Before developing our framework further we want to introduce a brief discussion on BE itself, since our LCSA is tailor-made for an application in BE assessment and monitoring.

4. Bioeconomy Under Changing Paradigms

4.1. A Changing Bioeconomy Discurse

Regarding our previous considerations about neoclassical and environmental economics, BE as a knowledge-based use and valuation of biological resources for commercial and industrial purposes (Birner, 2018) can be interpreted as both: a variable production factor technology as well as (additional) natural resources to be used. Therefore, BE was mainly seen as the appropriate endogenous technology factor and immediate precursor in the neoclassical concept of SD by providing sufficient resources and using them efficiently to increase benefit and profit maximization. The notions and political BE discourses in the EU were dominated by biotechnology visions from industrial stakeholders (Bugge et al., 2016, Staffas et al., 2013), i.e., striving to increase economic growth by using bio-resources (Liobikiene et al., Hausknost et al., 2017). Our preceding discussion of economic concepts and sustainability makes clearer why there is such a technological focus on BE: in all economic concepts but especially in the still dominating neoclassical ones, innovations and backstop technologies as well as substitution play a decisive role for maintaining growth and the further accumulation of natural capital.

This led to a major environmental frame of a BE: firstly boosting the economy and secondly benefiting the environment (Kleinschmit et al., 2017). This supposed win-win idea of the BE (Kleinschmit et al., 2017), strongly corresponding to the named concepts of weak sustainability, GE and GG (Liobikiene et al.), also results in weak-sustainability environmental policy integration in BE policy goals and strategies (Kleinschmit et al., 2017). Most of the many papers discussing the role of sustainability in BE criticize the technological focus and the disregard of environmental as well as excluding society and socioeconomic effects (Gawel et al., 2019, Pfau et al., 2014, Kleinschmit et al., 2017, Dietz et al., 2018). Especially the majority of NGOs have a critical perspective on BE and see this concept mainly as a PR campaign from industrial business to green-wash their business as usual (Gerhardt, 2018). In fact, a particularly conspicuous aspect is that sustainability has been addressed regularly, but seldom defined or specified as we will approach it in this work (Pfau et al., 2014, Gawel et al., 2019). In addition to ecological risks, there are also economic and social risks result from an intensified and increasing use of biobased resources (Siebert et al., 2016) as well as their shift to other countries through imports and a competition with the production of food in terms of product and land use (Suwelack, 2016, Ashukem, 2020). A biotechnology as a high-tech sector may raise huge sustainability risks when it is upscaled to an industrial level, and will absorb large-scale biomass streams demanding significant exports and imports (Bringezu et al., 2020, Gawel et al., 2019). These aspects may be a reason for the still low public awareness or critzism of the BE (Stern et al., 2018, Mustalahti, 2018). But it is the very acceptance, sustainability and societal desirability as well as the mutual understanding, level of knowledge and engagement of stakeholders which are decisive for its success (Pyka and Prettner, 2018, Zeug et al., 2019).

Nevertheless, a climate-neutral economy will depend on these enormous material flows of sustainable and renewable biomass and their material-energetic use integrated into the system. Unique about the BE provisioning system is its inherent capacity of regeneration, allowing natural or biological resource stocks to replenish after extraction, and they are typically in constant interaction with their surrounding systems (Lindqvist et al., 2019, Zörb et al., 2018). Whereas every unit of non-renewable resources used now, is a resource which will not be available in the future and thereby comprising intra- and intergenerational equity (Parrique T., 2019, Fedrigo-Fazio et al., 2016). But the BE socio-ecological system is only renewable and sustainable if: the rate of extraction does not exceed the rate of regeneration; the regenerative capacity is not diminished by extraction, processing, and utilization of the resource; and human needs are fulfilled as well as well-being is achieved by its economy practices. In contrast to non-renewable fossil systems, these complex interactions make the management of the BE complex and require fundamentally different strategies (Lindqvist et al., 2019). The main limiting long-term factors of the BE will be the conversion efficiency of 1–2% of plants turning sunlight into carbon; and the limited areas where sun shines, sufficient water is available and plants can grow without causing negative feedbacks like accelerating forestry erosion or soil erosion. A growing BE in Europe has already led to an abrupt increase in harvested forest area since 2015 and may hamper forest-based climate mitigation if it keeps up like this (Ceccherini et al., 2020).

Thus, a transition towards a sustainable BE implies a profound re-coupling of complex social and natural systems, which requires fundamental changes not only in technologies, but also in societal, economic, cultural and political conditions (Birner, 2018). Consequently, in recent years, BE is no longer seen only as a technological vision, but increasingly as a diverse set of political and economic concepts (Peltomaa, 2018, Hausknost et al., 2017). The focus of BE has switched from substitution to additional turnover and production due to declining fossil resource prices and back again (Birner, 2018). Beyond ecological benefits, our previous research showed that addressing societal challenges and not just to substitute a resource base is a major concern of relevant stakeholders (Zeug et al., 2019). So an urgently needed innovation is not only an extension of the fossil resource base by additional products, additionally valorizing and tending towards overexploitation of the biosphere (Lewandowski et al., 2018). But to aim for innovative products, technologies and provisioning system based on renewable resources, which at least can substitute the most disadvantageous fossil production systems in the medium term (e.g. by biofuels in aviation, bioplastics, wood in construction sector), reduce environmental impacts and simultaneously fulfill human needs as an end. This does not mean that there is a contradiction between substitution and innovation. On the contrary, innovation is one of the prerequisites for substitution. Beyond economic substitution, for most of the biophysical–social indicator linkages diminishing marginal utilities were identified: from a certain degree of affluence and fulfillment of human needs every additional unit of resource use contributes less to social performance, making sufficiency an essential factor for economic sustainability (O'Neill et al., 2018). Thereby the concept of reduce, reuse and recycle can actually be put into practice in the right order, since today a reduction or sufficiency of production and consumption is often not part of political BE strategies.

Therefore and because of the global challenges to be addressed, BE is inter- and transdisciplinary researched as a societal change aiming for social, political and economic sciences to deal with the necessary transformation processes (Center for Development Research (ZEF), 2018, Schütte, 2018). The perspectives on BE have been expended to all pillars of sustainability and economic, environmental and social aspects have at least been taken into account in concepts, narratives, political strategies and assessments (Liobikiene et al., Gawel et al., 2019). A sustainable BE not only can address several global challenges (Lewandowski et al., 2018, Schütte, 2018), rather it has to, to gain long-term social and political acceptance and to become established. Such meta-discourses are significantly effecting the BE and the recent trend within the European BE policy, strategies and narratives implies that the sustainability meta-discourse should be placed in the very core of BE (Takala et al., 2019). Transitioning to a sustainable BE entails more than tapping new growth or only substituting fossil inputs by renewable resources, which means the BE concepts have to be shifted from a solely technological to a more socio-technological focus (Gawel et al., 2019). Whether the resource base of the bio-economy is sustainable is doubted and credibility and acceptance of the BE can only be achieved when the absolute environmental and social benefits of bio-based products are proven (Gawel et al., 2019). Thus, not only economic institutions, organizations, and production techniques, but rather societal structures are currently seen as a major challenge of a dynamic BE (Dietz et al., 2018, Knierim et al., 2018).

In summary the BE discourse remains highly dynamic, ranging from an early technological focus win-win BE to newer concepts of BE as a complex societal change entailing a number of contradictions (Ronzon and M'Barek, 2018, Lindqvist et al., 2019, Balkau and Bezama, 2019): unclear or implicit means and ends; economic growth leading to increasing environmental impacts vs. the ecological necessity of reducing environmental impacts (Staffas et al., 2013, Spaiser et al., 2017, El-Chichakli et al., 2016); concurrency in land and resource use between nutritive, energetic and material use (Pfau et al., 2014, van Renssen, 2014, Ashukem, 2020); short-term achievements and long-term sustainability (Griggs et al., 2013, Future Earth, 2016); regional and global effects on different scales (Kleinschmit et al., 2017, Gao and Bryan, 2017, O'Keeffe et al., 2019); trade-offs among economic, ecological and social effects; shifts to other countries and regions through in- and exports as well as re- and backfire effects.

4.2. Bioeconomy Strategies and Policies

The updated BE strategies of the EU in 2018 (European Commission, 2018) and of Germany in 2020 (BMBF and BMEL, 2020) are steps forward in the direction of a holistically sustainable BE by aligning the strategies to maximize their contribution to several of the SDGs (SDGs 2, 7, 8, 9, 11, 12, 13, 14, 15) as well as the Paris Agreement. However, still neither the German nor the European BE strategy is well defined and deep-seated, they do not entail specific actions for a real transition towards sustainability and economic issues seem to be far more important than ecological or social issues (Gawel et al., 2019). Nevertheless, there are increasingly clear ambitions by officials and ministries fostering even more holistic and systemic perspectives and solutions using the SDGs as a framework for implementation (Schütte, 2018). The question remains how politics can foster the development of a sustainable BE in first place by means of bio-based research, product subsidies, changes in regulatory frameworks or increasing societal participation an awareness for a more sustainable production and consumption (Dietz et al., 2018, Gawel et al., 2019). Conflicting goals of the BE, far beyond the original 'food versus fuel' debate, represent the second major challenge of a sustainable BE framework (Dietz et al., 2018). Finally, the EU's Green New Deal strives to put decoupling, a social and economic transformation, SDGs, (regional) bio- and circular-economy, stakeholder participation, transdisciplinary research as well as social, environmental and economic sustainability at the heart of the EU's policy making and actions from 2020 on (Commission, 2020). Applying all these aspects to economic activities in specific sectors on a local level is difficult and will always be complex and political (Fedrigo-Fazio et al., 2016, de Schutter et al., 2019), and thus leads to the need for a scientific discussion and assessment of these risks and opportunities.

In recent years a specific political focus has been set on regional BE strategies, regional development and regional assessments like LCAs and LCSAs (European Commission, 2019, de Besi and McCormick, 2015, Bezama et al., 2017, Smetana et al., 2017). Main drivers for this, especially in industrialized and urbanized countries, are fostering rural development and revitalization, the advantages of local and decentralized production in saving transportation, increasing options for reuse and recycling, flexible and local development stimulating small-scale production, as well as social benefits through local employment and a fairer distribution of incomes (Pfau et al., 2014, Siebert et al., 2018). Focusing on specific regions allows better adaptation to regional characteristics, such as feedstocks or the knowledge of local stakeholders and their networks (de Besi and McCormick, 2015, Pfau et al., 2014). A better or even starting collaboration with a variety of stakeholders can bridge the gap between science and society, and can link up with societal infrastructure and public interest (Pfau et al., 2014). Thus, new research programs on BE foster communication and participation of all stakeholders (Schütte, 2018).

Considering that critical environmental impacts are related to food and energy BE activities, the import potential for additional non-food purposes in industrialized countries is limited under previous conditions, because in low income countries those capacities fulfil fundamental human needs with substantive products and services (de Schutter et al., 2019). On the other side, as BE-related deprivations in high income countries have been identified overconsumption, degradation of globally coupled ecosystems, and growing inequalities in the rural-urban context [ibid.]. From a progressive governance perspective the BE and its development can be characterized as a typical low-carbon transition which entails not only technical changes, but also changes in consumer behavior, markets, institutions, infrastructure, business models and cultural discourses (Geels et al., 2016). Consequently, BE is a case for integrated assessment models (IAMs) like LCSAs and studies regarding the BE have to make the social and political contextual factors with respect to the choice and implementation of a technology path more explicit (Schubert et al., 2015, Geels et al., 2016).

In a nutshell, chapter 4.1 and 4.2 show that the technological options and innovations of BE are more and more seen within a vision of a societal transformation towards sustainability. This is due to the several environmental, social and economic challenges adressed by the SDGs which have to be addressed. In this regard, LCSAs are not only necessary for assessing the BE, but the BE as a research object proposes diverse methodological challenges for LCSAs.

5. A Transdisciplinary Framework of Holistic and Integrated LCSA for the BE

Not surprisingly, setting up a new LCSA framework and model of ecological, social and economic sustainability assessment for regional BE is a very complex task in view of the problems outlined above. The high expectations that are placed on a BE as a technological and social innovation that can assert itself socially and politically are: maintaining and rebuilding natural capital as well as maintain and improve the quality of life for a growing world population at the same time (El-Chichakli et al., 2016). As an overarching goal, we are arguing for an BE-framework that aims for providing “a good life for all within PB” (O’Neill et al., 2018). In the following, we address the identified problems by introducing the SDGs as a normative goal system of holistic sustainability, make principles of transdisciplinary research applicable for LCSA, introduce the Societal Relations to Nature (SRN) as a well-founded theory of holistic sustainability and present a framework of holistic and integrated LCSA (HILCSA) based on these.

5.1. Integrating SDGs as a Normative Goals System

There is a growing consensus that the SDGs are an appropriate global framework of goals and a guiding system for SD available and are increasingly becoming an overarching topic in BE strategies, policies, and assessments (e.g. (BioMonitor, 2018, Calicioglu, forthcoming)) (Zeug et al., 2019). In this context the SDG subgoals and indicators are aspired to become an international, harmonized and comprehensive set of 230 global indicators, and although many obstacles have to be overcome, good data and clear metrics are critical (Schmidt-Traub et al., 2017). Nevertheless, sustainability research should not only be about good data, but about evidence that allows practical decision making towards more sustainability (Shepherd et al., 2015, Bezama, 2018).

However, the SDGs represent a general global political agenda and cannot be applied directly to BE. They mainly contain elements of holistic SD, but are presented as separate and not fully integrated (Nilsson and Costanza, 2015), implicitly interdependent, with complex synergies, trade-offs, and contradictions also depending on regions (Nerini et al., 2019, Nilsson et al., 2016). On the one hand there are dependencies, like climate change (SDG 13) on agricultural production and thus on reduce poverty and hunger (SDG 1, 2). Climate change, in turn, has a number of further social effects on e.g. increasing gender inequality (Nerini et al., 2019). On the other hand, narrowed policies on tackling climate change can lead to adversely effects on communities and SD (Nerini et al., 2019). Accordingly, a BE transformation implies possible risks and chances regarding the SDGs, e.g. food security (SDG 2) can increase via higher yields and new production methods, but decreased by higher food prices; poverty and inequality (SDG 1, 10) can be reduced by technology transfer and leapfrogging but also increased by economic exclusion (Ashukem, 2020); natural resources (SDG 7, 14, 15) can be conserved by improved production methods and degraded through inefficient production and overuse; climate change (SDG 13) can be mitigated by emission reduction or exacerbated through direct and indirect land use changes (Dietz et al., 2018). In general, the SDGs combine policy ends with means without proposing a hierarchy (Schmidt-Traub et al., 2017) and should be implemented as a set in a simultaneous and not sequential manner (Lubchenco et al., 2015).

In this regard the SDGs serve more to identify the most important normative aspects, drivers, and hotspots and therefore need to be selected and weighted for LCSA. This is important, since most strategy papers somehow consider ecological and socioeconomic sustainability aspects of the BE, but they hardly define concrete objectives and how these will be measured (Wesseler and von Braun, 2017). On the other hand, recently it was shown that goal systems and indicator frameworks of S-LCA approaches like RESPONSA are developed in a particular context and tend to cover only a few social SDGs, but then very intensively (Jarosch et al., 2020). Nonetheless, not every SDG indicator of global relevance necessarily plays a role in regional BE assessments, even when external or international effects are considered. Most suitable an identification of relevant SDGs and aspects is a systematic stakeholder participation from the beginning, which in general can play an important role in addressing persistent societal problems in a credible, transparent, and multi-perspective way (Bezama, 2018, Gerdes et al., 2018). In specific, a poor coherence between decision makers, scientists, and stakeholders was assessed to be at the origin of regulatory failures (European Commission, 2012, Dupont-Inglis and Borg, 2018), and biotechnology was and is the subject of controversial public debates, making societal acceptance an enabling factor (Meyer, 2017, Małyska and Jacobi, 2018). In our previous study (Zeug et al., 2019) the most important SDGs for the stakeholders involved were identified and quantified by dimensionless scores of relevance in the following descending order: ending hunger (SDG 2); sustainable consumption and production (SDG 12); terrestrial ecology (SDG 15); oceanic ecology (SDG 14); water and sanitation (SDG 6); climate change (SDG 13); affordable and clean energy (SDG 7); industrialization, innovation and infrastructure (SDG 9); no poverty (SDG 1). Sometimes volatile topics of medial narratives have a strong influence, and more important aspects also came up in the discussion of the stakeholders: (a) that the concerns of stakeholders about BE-sustainability are far beyond local ecological concerns; (b) the awareness of global environmental effects, international trade-offs, and big societal challenges such as hunger, poverty, and inequality is rising, (c) but also that there are strong particular interests by business stakeholders in contrast to more universal interests by society and science stakeholder.

Nearly all of the SDGs identified as important for the BE and vice versa are SDGs developing difficultly: (SDG 1) poverty declines but the goals will not be reached; (SDG 2) hunger is rising again due to various reasons; (SDG 12) consumption and productions patterns remain unchanged at a global level, the global material footprint is rapidly growing and economic growth and natural resource use are far from being decoupled; (SDG 13, 14, 15) only marginal ecological achievements were made and in many areas like biodiversity loss, deforestation and climate change the development is alarming; (SDG 6, 7, 9) infrastructures, sanitation, water and energy are developing comparatively good (UN, 2019b). As well nearly all of the SDGs have in common that their development is highly unequally distributed around the world and thereby also defining regional risks for a developing BE to address. But also chances of SDG-aligned BE outcomes are most likely to emerge at the sub-national level of society, since a multi-sector and multi-actor perspective can support social and technical innovations of urban and rural communities (de Schutter et al., 2019, Kuhmonen and Kuhmonen, 2015).

However the SDGs themselves aren't guided by a founded theory and neither provide a understanding of societal and natural systems, nor they incorporate a narrative of transformation, nor a means-ends-continuum or an ultimate-end the goals and targets are proposed for (Nilsson and Costanza, 2015, Costanza et al., 2014). Therefore the SDGs only represent a transformative development pathway to a limited extent. More scientific approaches to the refinement of the framework are needed as well as a systematic means-ends separation between ultimate goals, to attain human wellbeing in the long term depending, and an enabling development like global public goods, resources and capital (Nilsson and Costanza, 2015). This complexity of achieving sustainability across multiple social, economic and environmental dimensions entails a series of trade-offs and synergies between targets, interventions and policies, differing between countries, spatial scales, and timeframes. Some of these trade-offs will remain independently from smart policy measures and a socio-economic system, e.g. through finite resource constraints (Gao and Bryan, 2017). Other progressive developments, like socio-economic development by health programs and government spending or the decoupling of violence and inequality, are possible without these constraints (Spaiser et al., 2017). Empirically, by means of the SDGs it was shown that there are contradictions between human well-being and nature as PB, which can only be solved by global transformations (UN, 2019a). For our development and application of an HILCSA framework, the SDGs mainly set a comparable and legitimated normative holistic goal system and impact categories with additional possibilities in future data acquisition.

5.2. Transdisciplinary as a Consequence of Research on Sustainability

The need for a transdisciplinary sustainability science aiming at understanding interactions between nature and society has often been stated in the literature, but rarely substantiated or implemented (Pfau et al., 2014, Future Earth, 2016). One reason for this is that transdisciplinarity is a necessary consequence rather than a founding principle of such approaches like in sustainability sciences (Rhyner, 2016, Bettencourt and Kaur, 2011). A lot of knowledge and evidence of relationships (e.g. between SD and climate action) are scattered across different institutions, locations and disciplines, and this fragmentation is a critical barrier to a holistic and integrated understanding of the social–environmental systems embodied in the SDGs (Nerini et al., 2019, Knierim et al., 2018). The methods and findings of different scientific disciplines are oftentimes very rational, competent and innovative within their respective fields of expertise, but neglect or contradict insights from other disciplines (Demirovic, 2003). We understand interdisciplinarity as an interchange and dialogue between disciplines, whereas transdisciplinarity aims for integration: an inherent contextualization and embedding findings within a greater context creating transcending insights (Klein, 2008, Knierim et al., 2018, Lubchenco et al., 2015). Real-world problems are the starting point of transdisciplinary research, to gain a better understanding of social-ecological problems and contribute to their solution is the research objective (Kramm et al., 2017, Jahn et al., 2012). Of course modern science is much too complex to be covered by one person and so transdisciplinary practice means at least to work together, recognize each other and involve stakeholders to develop novel conceptual and methodological frameworks with the potential to produce transcendent theoretical and practical approaches (Hummel et al., 2017, Klein, 2008, Rosenfield, 1992). The resulting methodological pluralism, can lead to more consistencies and less bias (Lamont et al., 2006). In recent years often used is the term of "socio-economic" systems or problems, which is a good example for transdisciplinarity: the attributes 'social' and 'economic' do not describe separate objects of scientific observation, but rather different perspectives on the same objects, whereas a socio-economic approach describes the integration of both perspectives when looking at this object. And it is of specific importance for LCAs and LCSA, since companies are not just producers of commodities and services, they are also the fundamental social place, where employment is organized, employees are being integrated into a social structure, and where individuals are connected with the labor market and systems of social security (soeb.de, 2020).

In the case of presenting a framework for holistic sustainability assessments with a systematic view on a developing regional BE, transdisciplinarity means to understand a seemingly ecological project or research question as a simultaneously political-economic project and research question and vice versa. Consequentially, ecological arguments can never be neutral any more than sociopolitical arguments are ecologically neutral (Harvey and Braun, 1996). This means for achieving a sustainable transition to a BE, there is not only a need to transform so called societal and industrial mind-sets, and not only a question of a few ‘tweaks’ to the system, but rather it is a question of transformations of our very fundamental societal relations to nature (SRN) (de Besi and McCormick, 2015, Kramm et al., 2017). Different means, ends, and values seem to be the guiding factors in what we have understood as conflicting interests and perceptions in BE assessments (Zeug et al., 2019). Simply setting ambitious goals, but ignoring ideologies, religious beliefs and institutions, including formal and informal rules and customs will not be sufficient (Norström, 2013). Since only technological fixes, a solely focus on industrial efficiency or simply replace fossil resources with biomass are in danger of maintaining the same production and consumption system as the fossil-based economy (de Besi and McCormick, 2015). Such insights go back to the early interdisciplinary materialism, later critical theory and social ecology and are applied in the concept of SRN. They reveal that there is no non-normative science; if there is no explicit scientific value judgement there is an implicit social value judgment confirming the status quo (Kramm et al., 2017, Hummel et al., 2017, Amidon, 2008). Regarding the IAMs of low-carbon transition, the following framework approach is still using post-positivist methods of modelling, but embeds them into a relativism and postmodernism philosophy of science, and thereby combines the strengths of quantitative systems modelling, socio-technical analysis and initiative-based learning by stakeholder participation. A combination of all three approaches is not trivial, but is most promising for IAMS of transitions (Geels et al., 2016). Transdisciplinarity is therefore necessary to achieve a proper integration of methods in an LCSA.

5.3. Societal Relations to Nature as a Founded Theory

As shown in section 3.1, none of the dualistic approaches alone is sufficient, neither anthropocentric nor ecocentric, neither weak nor strong sustainability, and especially not the dominant and reductionist model of sustainability. But rather the integrated model and a corresponding holistic thinking based on the interactions and relations between the parts and the whole. Therefore, we take up the concept of SRN towards a holistic LCSA of the BE. In SRN nature, economy and society do not stand in an external relation to each other nor do they exist by themselves as the three-pillar approach suggests, rather, they constitute each other through their relations (Kramm et al., 2017, Hummel et al., 2017, Görg et al., 2017, Görg, 2003): The SRN concept at its core evolves around the idea of basic human needs and SRN should be regulated to satisfy them. Thus, SRN is not only complementary and a well-founded theory for the SDGs, but also incorporates the concept of provisioning systems, justice (Menton et al., 2020), equity, and SD. Social ecology and SRN conceptualizes human societies as simultaneously subject to biophysical and socio-cultural spheres of causation in a social metabolism. Nature and society are different things, and although distinct, not independent from one another. Social metabolisms transform a society’s energetic and material inputs, integrate them into societal stocks or to other socio-economic systems, and discharge them to the environment as wastes and emissions. Industrial and BE metabolisms are special cases of social metabolisms. In well-established methods like economy-wide material and energy flow accounts (EW-MFA) societal metabolisms at the European level have been quantified and measured. However, this societal metabolism has no essential or eternal nature, especially not in the Anthropocene (Pichler et al., 2017). Instead historically, geographically and culturally specific socio-cultural mechanisms like politics and economic patterns are in place through which a society organizes its metabolism. This is decisive for SRN, not the sum of individual needs.

These mechanisms are understood as patterns of regulation, and of course can fail when interactions with nature become dysfunctional, e.g. overexploitation of natural resources (overfishing, deforestation, soil degradation) or failure of a mechanism for cost-efficient provision (hunger, poverty). Although there is the idea of being able to dominate nature, and nature is in fact increasingly shaped by human activities, it is becoming increasingly clear that global societies are significantly affected by environmental impacts and crisis trends. Albeit, in unequal measure in the Global South and the Global North. It doesn't apply to all SRN, but the dominant mode is the imperative of capital accumulation, growth and the predominance of the production of surplus values over the production of use values, whereby the production of surplus values goes hand in hand with the valorization and overexploitation of its capital (nature and humans). Transformations take place as changes of initial patterns of regulation to new ones when the old ones become dysfunctional. The SDGs can be interpreted as the attempt to initiate such social-ecological transformations. The role of power relations in enabling and maintaining unsustainable resource use patterns, the role of social-ecological innovations within transformation processes and transregional interdependencies have been identified as emerging clusters of challenges in societal metabolism. For example, technological inventions must go hand in hand with social, economic and organizational innovations, and questions of scale arise in the field of tensions between a global socio-ecological crisis and the responsibility and scope for action at local and regional level. Therefore, the view of a separation of LCSA and global macroeconomic-political problems as in the additional LCSA approach is criticized.

In terms of scales SRN have three different spatial and temporal levels which correspond to the scales and scope of BE assessments (Figure 1): the micro level of individual actions; the meso level of organizations and institutions (provisioning systems); and the macro level of societal powerful patterns of regulation. In our case of BE we focus on the meso level of provisioning systems, which link natural objects (e.g. forests) to the societal realms of action and decision-making via the utilization of resources. Putting SRN into research practice means to identify a case consisting of an issue and a problem. Here the issue is a developing regional BE having social and ecological effects. The problem is that there are risks and chances of such a BE for implementing the SDGs. Finally, the scientific goal is to decontextualize or generalize the case knowledge produced to make conclusions for solving a problem of an issue. Progress has been made in recent years to empirically and quantitatively describe socioeconomic metabolisms by EW-MEFA on the macro scale, also for addressing decoupling problems (Haberl et al., 2017). Although, on the meso scale (e.g. through LCAs) the concept of SRN and socioeconomic metabolisms has not been applied so far. Besides absolute global PB, there are also regionally specific local boundaries (e.g. biodiversity, land-use changes). For such a relation of local boundaries with holistic regional sustainability framework and LCSAs, the concept of ecosystem services (ES) in context of SRN and social ecology is promising.

ES concepts are neither about ecosystems nor about societal goods and human wellbeing solely, but about the interdependencies between human wellbeing (benefits) and nature when ‘natural ecosystems’ are transformed into human-modified cultural landscapes by human interventions (labor, technology). Additionally, ES are also open for stakeholder participation and finding these regional boundaries through non-monetary evaluations. On a regional scale transdisciplinary approaches offer new possibilities of deliberative methods to find normative constellations of human needs by stakeholder participation (e.g. interviews and discussions). On the contrary, solely monetary approaches or the search for a big number have failed (e.g. TEEB (Tisdell, 2015)). This is because goods or services have a use value when they fit human needs and create a benefit depending on specific cultural value systems. Monetary exchange values in capitalist societies, however, are governed by exchange relations on global markets. And thus, tend to ignore the relevance of regional ecosystems and nature for the actual benefits they provide. Both values use and can overuse resources, but monetary or exchange values tend to ignore the biophysical requirements of ecosystems categorically (Schleyer et al., 2017). Common to both values, and especially important for HILCSA, is that working hours are the critical functional variable in the production processes of provisioning systems, which not only produces values but also relates social effects to productions processes (Fröhlich, 2009).

In this regard a good example of SRN and patterns of regulation which are behind the SDGs is the apparent connection between ending poverty (SDG 1) and ending hunger (SDG 2), both considered by stakeholders as very relevant for the BE (Zeug et al., 2019). In this case, even if enough food is produced worldwide to end hunger, the pattern of regulation of our provisioning system requires ending poverty first. Since in the current economic system human needs alone (use value), sufficient resources and means do not lead to their fulfillment, as long as those needs and preconditions are not coupled with enough purchasing power and income (exchange and surplus value). The same is true for the fuel vs food debate in BE: land or crops will be used for the purpose with the highest expected surplus value like fuels, instead of the fulfillment of more basic human needs with a higher use value like nutrition (cf. (Ashukem, 2020)). Beyond that, SRN include socioeconomic relations like the decoupling between a significantly increasing labor productivity and economic material output through automatization and digitalization, but a stagnation and even falling of GDP per capita, private employment and even more so in income and inequality, especially in affluent and industrialized countries (Brynjolfsson and Andrew, 2015). But also globally the labor’s share of GDP had declined since there is a tendency towards higher capital productivity in capital than in labor and so shifting the investments from labor to capital (Karabarbounis and Neiman, 2013). When a growing economic production and material output is not decoupled from its ecological impacts, but income and affluence is decoupled from this very production, then a good life for all within PB will be hard to achieve when income is a prerequisite for achieving nearly all social thresholds.

For our purposes the SDGs represent a limited number of universal and satiable human needs as well as their means (Figure 5). The fulfilment of such needs provides conditions for wellbeing in the broader context of society, and if unsatisfied should be understood as deprivations (de Schutter et al., 2019). Consequently, as for every economy, the end of the BE should be the fulfillment of human needs. Earlier, it was argued for putting human needs and well-being in the center of LCSA, but from an anthropocentric viewpoint with rather conceptual ideas (Schaubroeck and Rugani, 2017, Schaubroeck, 2018). However, in our framework of LCSA based on SRN, social sustainability means the fulfillment of human needs as the end and ultimate goal of an ecological sustainable BE within planetary boundaries, which also implies the transformation of patterns of regulation and SRN.

5.4. A Background Framework for Holistic Life Cycle Sustainability Assessments

We identified the three pillar approach (section 2.2) and the underlying dominant reductionist model of interlinked systems (section 3.2) as inappropriate for an integrated and holistic LCSA as well as a cause of major methodological problems. Instead, first, we propose an integrated sustainability framework filling the identified research gap of a missing framework for HILCSA (Figure 4, i)). Second, in contrast to the additive LCSA (LCSA = S-LCA + E-LCA + LCC), our HILCSA (HLCSA = f (S-LCA, E-LCA, LCC)) framework for operationalization will build on this integrated sustainability framework and integrates social, economic and ecological aspects in a common goal and scope, life cycle inventory, impact assessment, results and interpretation (Figure 4, ii)).

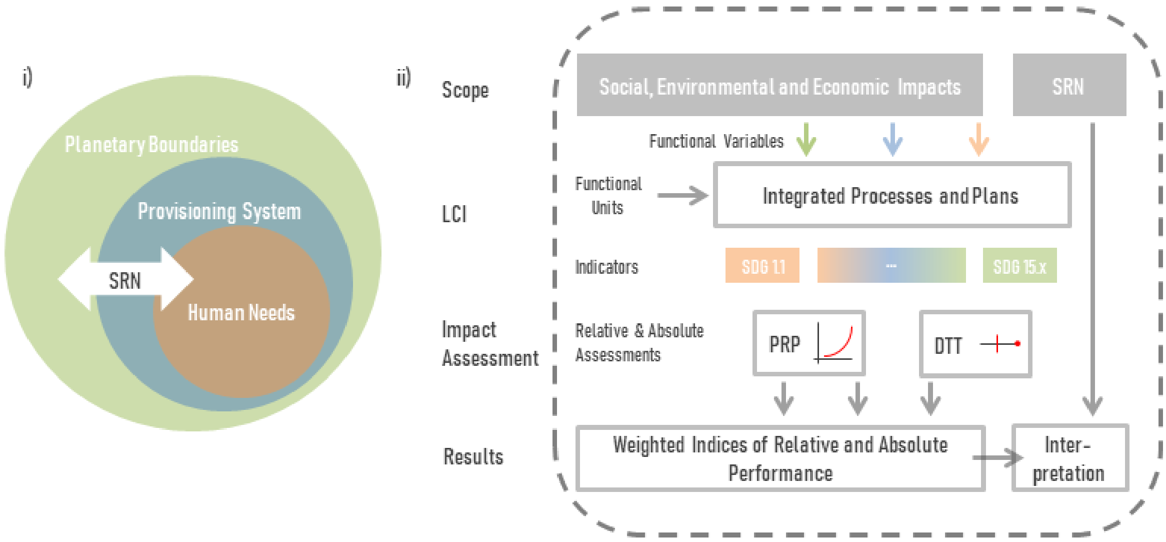

Figure 4, i) The integrated model of holistic sustainability in LCSA based on the SRN, ii) Holistic and integrative scheme of HILCSA (HILCSA=f(S-LCA,E-LCA,LCC)) based on i) (SRN - Societal Relations to Nature, PRP – Relative method of impact assessment by Performance Reference Points, DTT – Absolute method of impact assessment by Distance To Target, LCI – Life Cycle Inventory)

In the following, we mainly discuss the integrated sustainability framework based on our reflection on sustainability concepts, the SDGs and transdisciplinary application of the SRN (Figure 5).

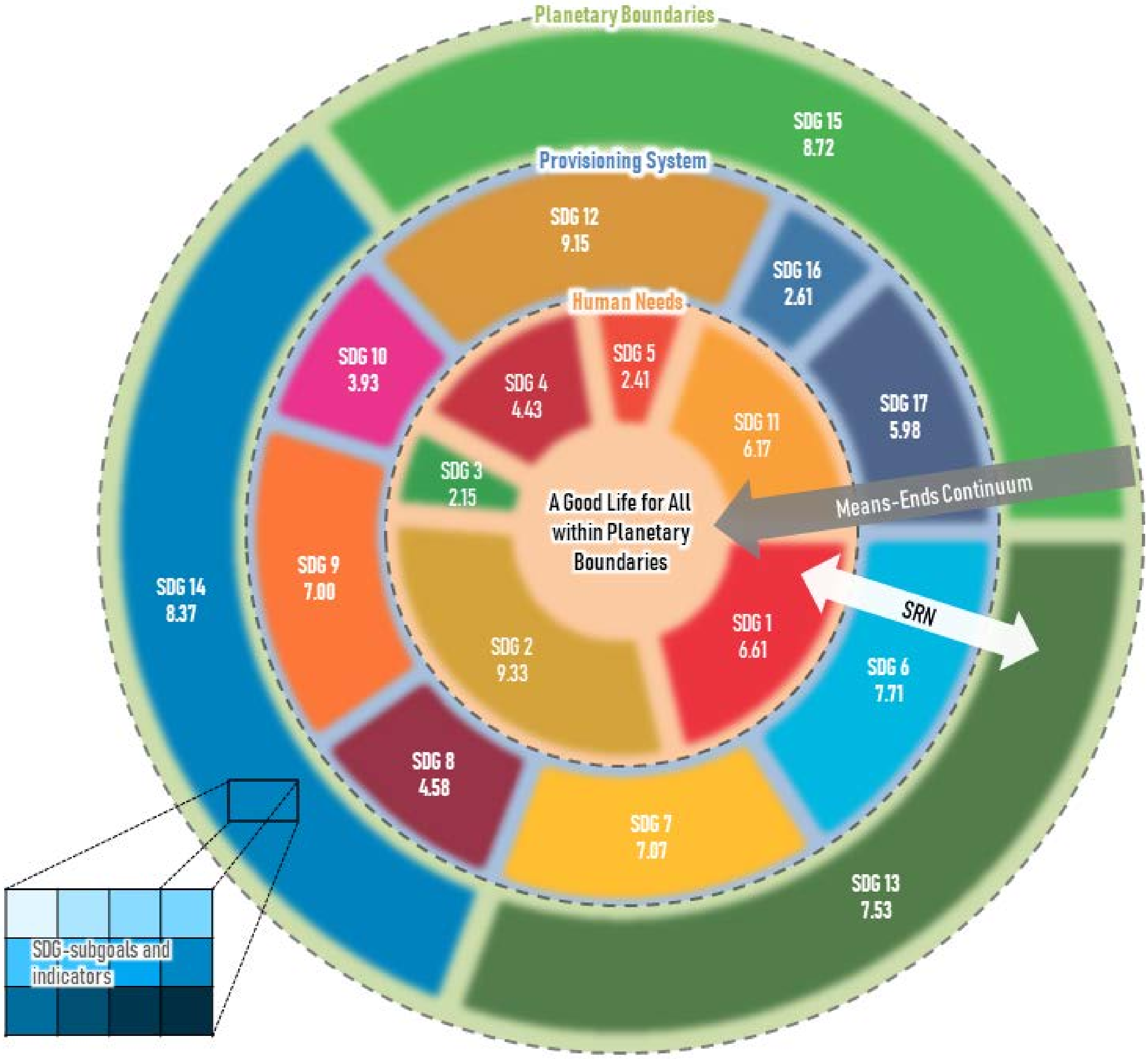

Figure 5, Holistic sustainability framework for HILCSA of the BE (SDGs are viewed with their relevance for German BE assessments from (Zeug et al., 2019) and according size, for each SDGs the SDG-subgoals and indicators as well as their relevance is taken from (Zeug et al., 2019))

We understand the BE as an open or semi-open provisioning system of a social metabolism on the meso-level of SRN. Its function is to link social outcomes and renewable resource use by innovative technologies. BE comprises both physical and social systems, mediating the relationship between biophysical and social thresholds by economic networks of physical infrastructure. Besides political governance and the influence of stakeholders (science, organizations and corporations, NGOs, producers, consumers, local and global communities) on different levels, these relations are structured by markets as exchange platforms and as dominating pattern of regulation (in the current economy system of surplus and exchange values). Economic quality in this regard is understood as the relative and absolute efficiency, sufficiency and effectiveness of linking social and biophysical systems, which overall means to meet most of the social goals and thresholds with the lowest resource use possible (O'Neill et al., 2018) A sustainable regional bioeconomy should aim at the provisioning of a good life for all within global PB and regional boundaries. Hence, it corresponds strongly to the "Planned Transition" techno-political vision of BE (Hausknost et al., 2017). This means that on the one hand advanced technologies on a large-scale industrial level (integrated biorefineries, cascade use, eco-functional intensification of certain agricultural sectors, global trade in certain biogenic commodities, use of high-tech biotechnologies) will be needed to achieve the very ambitious demands on resource efficiency (Olsson et al., 2016, Nitzsche et al., 2016, Aguilar et al., 2018, Panoutsou et al., 2013). On the other hand, further growth and capital accumulation is not a necessary sustainable goal of the BE. Rather, not transgressing the PBs and fulfilling essential human needs and the SDGs (especially SDGs 1, 2, 7, 11 &12) are.

In specific, the characteristics of and relations between concrete aspects represented by SDG sub-goals and indicators will be analyzed and described for the application in our upcoming research on a regional HILCSA model. Due to the complex interactions, there can be no truly clean analytical distinction (de Schutter et al., 2019), but certain SDGs can be assigned to the following relations: the more efficient fulfillment of human needs as the end of a sustainable BE and all efforts are placed in the center (SDG 1, 2, 3, 4, 5, 11); BE and economy as a social activity and provisioning systems represents the societal means (technologies, infrastructures) which fulfill human needs by natural resources within PB, it relates social and natural systems (SDG 6, 7, 8, 9, 10, 12); the natural system as stock of renewable resources and their regeneration are placed as the limiting PB (SDG 13, 14, 15); institutions of the patterns of regulation are part of the provisioning system (SDG 16, 17). These relations represent the missing means-ends-continuum. The relevance which each of the SDGs has for the measurement and assessment of regional BE in Germany, in this case for HILCSAs, was evaluated by our previous stakeholder participation (Zeug et al., 2019) and is presented in section 5.1. In Figure 5 different relevances are represented by the different size of the SDGs relative to the other SDGs within the according social, economic or natural system (Appendix A).

This framework also makes clearer what can actually be understood by holistic and social environmental and economic sustainability:

- Social sustainability is the long-term and global fulfillment of human needs and social well-being as an end
- Ecological sustainability is the long-term stability of our environment as a basis of reproduction within planetary boundaries
- Economic sustainability stands for technologies and economic structures which are efficient, effective and just provisioning systems relating human needs and environment

Goal and scope of our HILCSA is to assess the social, environmental and economic risks and chances of a regional BE, its contributions to the SDGs and a sustainability transformation. Therefore a holistic scope and understanding is given by the SRN. Our focus is also on the comparison of bio-economy products made from renewable raw materials such as wood with other products. Regarding the LCI, the operational core of our model are integrated processes and plans of regional BE value chains and provisioning systems implemented in openLCA software environment. We will lay out the actual implementation and operationalization of our HILCSA in detail future publications. In this LCI, the relevancies of the SDG sub-goals determine the weightings of a future set of impact categories and indicators. At the first stage in a holistic assessment the indicator set will not be as detailed as in the stand alone methods, rather the goal is to avoid a piecemeal approach to SD (Taylor et al., 2017) and to deliver a holistic picture on trade-offs, synergies, hotspots, significant risks and chances and a fundamental understanding. The impact assessments will incoporate two types: relative performance of a particular BE system in relation to a fossil reference system (PRP); and the absolute benchmarking of a particular BE system against the SDGs and PBs (DTT). In contrast to the previous LCSA methods, where the separate and different results are at the end additively combined by MCDA, our SDG oriented HILCSA uses the relevancies of SDG sub-goals given by stakeholders as exogenous weightings of indices on different levels of aggregation according to the SDG framework. Decisive for the generation of indices in a systematic-interactionist approach like ours, but above all for the interpretation of those quantitative results is a comprehensive and well-founded theory of sustainability and a sustainable BE, which we provided in this work.

6. Conclusions and Outlook

Taking up the decoupling problem as a starting point of our consideration of BE and its assessment shows the need and potential of a sustainable BE for decoupling human well-being from environmental impacts to avoid a social and ecological crisis. Some nations show the ability of achieving the social thresholds at a much lower level of resource use, and give a sense of the possibility space for achieving the social thresholds within PB (O'Neill et al., 2018). However, considered all together, the decoupling hypothesis appears highly compromised, if not clearly unrealistic in a business as usual scenario (Parrique T., 2019). To strive for gains in technological efficiency is absolutely necessary, but alone not sufficient anymore and as well a societal change entailing the BE is necessary. Traditional additive LCSA approaches are valuable, but face major methodological and practical problems for assessing the BE. On the other hand, the SDGs can provide progressive measurable and normative targets and objectives for BE assessments, as well as transdisciplinary and well-founded theories like SRN consider human needs, provisioning systems and ecological boundaries not as separate entities, but rather as facets of one and the same object; the social industrial metabolism. This sets the basis and locks up potential for a holistic and integrative framework of HILCSA with a common scope, goal, LCI, functional units and variables, impact assessment and interpretation, which we will implement in forthcoming research. In the last step of interpretation, those results can be put in context to an ideal or desirable BE and the contribution of a regional BE for implementing the SDGs, risks, chances, synergies and trade-offs can be described. With special regard to a regional BE this can help to bridge the gap between science, society, politics and economic actors in public interest. Thereby we embed positivist methods of science into a relativist and postmodernist philosophy of science, which enables us to combine the strengths of quantitative systems modelling, socio-technical analysis and stakeholder-based learning. Applying the SDGs or absolute goals as PB in LCA, however, goes beyond established approaches and brings up methodical transdisciplinary challenges we will address in our upcoming research. Relative (PRP) as well as absolute (DTT) methods of impact assessment are proposed to allow results for comparing provisioning systems as well as to assess if a provisioning system is efficient enough for PB. As an indicator set the SDG indicators and Dashboards provide not only a harmonized basis for also consider trans-regional aspects but an ever improving data basis. A challenge will be that private industrial actors in a capitalist market have an intrinsic interest in capital accumulation and increasing output, and by themselves will not embark to the SDGs or PB. States are therefore the only entities able to provide the organizational and planning capacity by political coordination necessary for this transition (Hausknost et al., 2017). Corporations are still key actors, but guided by societal rules and strategies. For this, however, a necessary change of patterns of regulation is necessary in a way that states themselves are not depending on abstract economic growth, which has been identified by stakeholders as a relatively minor objective (Zeug et al., 2019).

However, the overall possibilities of achieving sustainability by BE are limited as long as sustainability is not a central objective of the general economy and its patterns of regulation itself. If the concept of a sustainable BE as a solution for global challenges is put at risk, a lot is at stake, because there will be no alternatives other than BE to produce the needed material goods from renewable instead of fossil resources.

References

AGUILAR, A., WOHLGEMUTH, R. & TWARDOWSKI, T. 2018. Preface to the special issue bioeconomy. *New Biotechnology,* 40**,** 1-4.

AMIDON, K. S. 2008. "Diesmal fehlt die Biologie!" Max Horkheimer, Richard Thurnwald, and the Biological Prehistory of German Sozialforschung. *New German Critique***,** 103-137.

ANAND, M. 2016. Innovation and Sustainable Development: A Bioeconomic Perspective *Brief for GSDR – 2016 Update.* New Delhi: The Energy and Resources Institute (TERI).

ASHUKEM, J.-C. N. 2020. The SDGs and the bio-economy: fostering land-grabbing in Africa. *Review of African Political Economy***,** 1-16.

BALKAU, F. & BEZAMA, A. 2019. Life cycle methodologies for building circular economy in cities and regions. *Waste Management & Research,* 37**,** 765-766.

BALKAU, F. & SONNEMANN, G. 2017. Synthesis - life cycle approaches and perspectives for sustainable regional development. *Life cycle approaches for sustainable regional development.* New York: Routledge.

BARBIER, E. B. 1999. Endogenous Growth and Natural Resource Scarcity. *Environmental and Resource Economics,* 14**,** 51-74.

BELL, J., PAULA, L., DODD, T., NÉMETH, S., NANOU, C., MEGA, V. & CAMPOS, P. 2018. EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions. *New Biotechnology,* 40**,** 25-30.

BETTENCOURT, L. M. & KAUR, J. 2011. Evolution and structure of sustainability science. *Proc Natl Acad Sci U S A,* 108**,** 19540-5.

BEZAMA, A. 2018. Understanding the systems that characterise the circular economy and the bioeconomy. *Waste Management & Research,* 36**,** 553-554.

BEZAMA, A., INGRAO, C., O'KEEFFE, S. & THRÄN, D. 2019. Resources, Collaborators, and Neighbors: The Three-Pronged Challenge in the Implementation of Bioeconomy Regions. *Sustainability,* 11**,** 7235.

BEZAMA, A., SIEBERT, A., HILDEBRANDT, J. & THRÄN, D. 2017. Integration of LCA, LCC, and SLCA methods for assessing a bioeconomy region. *Life cycle approaches to sustainable regional development.* New York: Routledge.

BIOMONITOR. 2018. *BioMonitor - Monitoring the Bioeconomy* [Online]. Available: http://biomonitor.eu/ [Accessed 20/12/2018 2018].

BIRNER, R. 2018. Bioeconomy Concepts. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.

BMBF & BMEL 2020. Nationale Bioökonomiestrategie. Berlin: Bundesministerium für Bildung und Forschung, Bundesministerium für Ernährung und Landwirtschaft.

BRACCO, S., CALICIOGLU, O., GOMEZ SAN JUAN, M. & FLAMMINI, A. 2018. Assessing the Contribution of Bioeconomy to the Total Economy: A Review of National Frameworks. *Sustainability,* 10**,** 1698.

BRINGEZU, S., BANSE, M., AHMANN, L., BEZAMA, A., BILLIG, E., BISCHOF, R., BLANKE, C., BROSOWSKI, A., BRÜNING, S., BORCHERS, M., BUDZINSKI, M., CYFFKA, K.-F., DISTELKAMP, M., EGENOLF, V., FLAUTE, M., GENG, N., GIESEKING, L., GRAß, R., HENNENBERG, K., HERING, T., IOST, S., JOCHEM, D., KRAUSE, T., LUTZ, C., MACHMÜLLER, A., MAHRO, B., MAJER, S., MANTAU, U., MEISEL, K., MOESENFECHTEL, U., NOKE, A., RAUSSEN, T., RICHTER, F., SCHALDACH, R., SCHWEINLE, J., THRÄN, D., UGLIK, M., WEIMAR, H., WIMMER, F., WYDRA, S. & ZEUG, W. 2020. Pilotbericht zum Monitoring der deutschen Bioökonomie. Kassel: Center for Environmental Systems Research (CESR).

BRUNDTLAND, G., KHALID, M., AGNELLI, S., AL-ATHEL, S., CHIDZERO, B., FADIKA, L., HAUFF, V., LANG, I., SHIJUN, M., MORINO DE BOTERO, M., SINGH, M., OKITA, S. & OTHERS, A. 1987. *Our Common Future ('Brundtland report'),* Oxford University Press, USA.

BRYNJOLFSSON, E. & ANDREW, M. 2015. The Great Decoupling. *Harvard Business Review.*

BUDZINSKI, M., BEZAMA, A. & THRAN, D. 2017. Monitoring the progress towards bioeconomy using multi-regional input-output analysis: The example of wood use in Germany. *Journal of Cleaner Production,* 161**,** 1-11.

BUGGE, M., HANSEN, T. & KLITKOU, A. 2016. What Is the Bioeconomy? A Review of the Literature. *Sustainability,* 8**,** 691.

CALICIOGLU, O. forthcoming. Linking the Measurement of Sustainable Bioeconomy Development to the Performance in SDG Implementation. Rome: FAO (Food and Agricultural Organization of the United Nations).

CECCHERINI, G., DUVEILLER, G., GRASSI, G., LEMOINE, G., AVITABILE, V., PILLI, R. & CESCATTI, A. 2020. Abrupt increase in harvested forest area over Europe after 2015. *Nature,* 583**,** 72-77.

CENTER FOR DEVELOPMENT RESEARCH (ZEF). 2018. *Bioeconomy as societal change* [Online]. Available: https://www.bioecon-societal-change.de/ [Accessed 07/05/2018 2018].

CHISTI, Y. 2010. A bioeconomy vision of sustainability…. *Biofuels, Bioproducts and Biorefining,* 4**,** 359-361.

COMMISSION, E. 2020. The European Green Deal - COM(2019) 640. Brussels.

COMMON, M. & STAGL, S. 2005. *Ecological Economics: An Introduction,* Cambridge, Cambridge University Press.

COSTA, D., QUINTEIRO, P. & DIAS, A. C. 2019. A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. *Science of The Total Environment,* 686**,** 774-787.

COSTANZA, R., CUMBERLAND, J., DALY, H., GOODLAND, R. & NORGAARD, R. 1997. *An Introduction to Ecological Economics,* CRC Press.

COSTANZA, R., KUBISZEWSKI, I., GIOVANNINI, E., LOVINS, H., MCGLADE, J., PICKETT, K. E., RAGNARSDOTTIR, K., ROBERTS, D., DE VOGLI, R. & WILKINSON, R. 2014. Development: Time to leave GDP behind. *Nature,* 505**,** 283-5.

D'AMATO, D., GAIO, M. & SEMENZIN, E. 2020. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. *Sci Total Environ,* 706**,** 135859.

DE BESI, M. & MCCORMICK, K. 2015. Towards a Bioeconomy in Europe: National, Regional and Industrial Strategies. *Sustainability,* 7**,** 10461.

DE SCHUTTER, L., GILJUM, S., HÄYHÄ, T., BRUCKNER, M., NAQVI, A., OMANN, I. & STAGL, S. 2019. Bioeconomy Transitions through the Lens of Coupled Social-Ecological Systems: A Framework for Place-Based Responsibility in the Global Resource System. *Sustainability,* 11**,** 5705.

DEMIROVIC, A. 2003. Vorwort. *In:* DEMIROVIC, A. (ed.) *Modelle kritischer Gesellschaftstheorie.* Stuttgart: J.B. Metzler.

DIETZ, T., BÖRNER, J., FÖRSTER, J. J. & VON BRAUN, J. 2018. Governance of the Bioeconomy: A Global Comparative Study of National Bioeconomy Strategies. *Sustainability,* 10**,** 3190.

DRESNER, S. 2002. *The Principles of Sustainability,* Oxford, Earthscan.

DUPONT-INGLIS, J. & BORG, A. 2018. Destination bioeconomy – The path towards a smarter, more sustainable future. *New Biotechnology,* 40**,** 140-143.

EDITORIAL NATURE SUSTAINABILITY 2018. Our common vision. *Nature Sustainability,* 1**,** 1-1.

EGENOLF, V. & BRINGEZU, S. 2019. Conceptualization of an Indicator System for Assessing the Sustainability of the Bioeconomy. *Sustainability,* 11**,** 443.

EKENER, E., HANSSON, J., LARSSON, A. & PECK, P. 2018. Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting - Tested on biomass based and fossil transportation fuels. *Journal of Cleaner Production,* 181**,** 337-351.

EL-CHICHAKLI, B., VON BRAUN, J., LANG, C., BARBEN, D. & PHILP, J. 2016. Policy: Five cornerstones of a global bioeconomy. *Nature,* 535**,** 221-3.

ELKINGTON, J. 1998. Partnerships fromcannibals with forks: The triple bottom line of 21st-century business. *Environmental Quality Management,* 8**,** 37-51.

EUROPEAN COMMISSION 2012. Innovating for Sustainable Growth: A Bioeconomy for Europe. Brussels: European Commission.

EUROPEAN COMMISSION 2018. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment - Updated Bioeconomy Strategy. Brussels: European Commission.

EUROPEAN COMMISSION. 2019. *Advancing the Creation of Regional Bioeconomy Clusters in Europe* [Online]. Available: Advancing the Creation of Regional Bioeconomy Clusters in Europe [Accessed 12/04/2019 2019].

FAUZI, R. T., LAVOIE, P., SORELLI, L., HEIDARI, M. D. & AMOR, B. 2019. Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment. *Sustainability,* 11**,** 636.

FEDRIGO-FAZIO, D., SCHWEITZER, J.-P., TEN BRINK, P., MAZZA, L., RATLIFF, A. & WATKINS, E. 2016. Evidence of Absolute Decoupling from Real World Policy Mixes in Europe. *Sustainability,* 8.

FRÖHLICH, N. 2009. *Die Aktualität der Arbeitswerttheorie - Theoretische und empirische Aspekte,* Marburg, Metropolis.

FUTURE EARTH 2016. *The contribution of science in implementing the Sustainable Development Goals,* Stuttgart, German Committee Future Earth.

GAO, L. & BRYAN, B. A. 2017. Finding pathways to national-scale land-sector sustainability. *Nature,* 544**,** 217.

GAWEL, E., PANNICKE, N. & HAGEMANN, N. 2019. A Path Transition Towards a Bioeconomy—The Crucial Role of Sustainability. *Sustainability,* 11**,** 3005.

GEELS, F. W., BERKHOUT, F. & VAN VUUREN, D. P. 2016. Bridging analytical approaches for low-carbon transitions. *Nature Climate Change,* 6**,** 576.

GEORGESCU-ROEGEN, N. 1971. *The Entropy Law and the Economic Process*.

GERDES, H., KIRESIEWA, D. Z., BEEKMAN, V., BIANCHINI, C., DAVIES, S., GRIESTOP, L., JANSSEN, R., KHAWAJA, C., MANNHARDT, B., MAZZARIOL, F., MILLAR, K., OVERBEEK, G., STOYANOV, M., UGALDE, J.-M. & VALE, M. 2018. Engaging stakeholders and citizens in the bioeconomy: Lessons learned from BioSTEP and recommendations for future research. Ecologic Institute.

GERHARDT, P. 2018. *Bioökonomie – die neue Nebelwand aus der PR-Abteilung* [Online]. Bremen: denkhausbremen. Available: https://denkhausbremen.de/biooekonomie-die-neue-nebelwand-aus-der-pr-abteilung/ [Accessed 19/11 2018].

GERMAN BIOECONOMY COUNCIL. 2018a. Available: http://biooekonomierat.de/en/ [Accessed].

GERMAN BIOECONOMY COUNCIL 2018b. Update Report of National Strategies around the World - Bioeconomy Policy (Part III). *In:* FUND, C., EL-CHICHAKLI, B. & PATERMANN, C. (eds.). Berlin: Bioeconomy Council.

GFN, G. F. N. 2019. *Ecological Deficit/Reserve* [Online]. Available: https://data.footprintnetwork.org [Accessed 05.09.2019 2019].

GÖRG, C. 2003. Dialektische Konstellationen. Zu einer kritischen Theorie gesellschaftlicher Naturverhältnisse. *In:* DEMIROVIC, A. (ed.) *Modelle kritischer Gesellschaftstheorie.* Stuttgart: J.B. Metzler.

GÖRG, C. 2004. The construction of societal relationships with nature. *Poiesis & Praxis,* 3**,** 22-36.

GÖRG, C., BRAND, U., HABERL, H., HUMMEL, D., JAHN, T. & LIEHR, S. 2017. Challenges for Social-Ecological Transformations: Contributions from Social and Political Ecology. *Sustainability,* 9**,** 1045.

GRIEßHAMMER, R., BENOIT, C., DREYER, L., FLYSÖ, A., MANHART, A. & MAZIJIN, B. 2006. Feasibility Study: Integration of Social Aspects into LCA. Paris, France: Department of Conflict and Development Studies.

GRIGGS, D., STAFFORD-SMITH, M., GAFFNEY, O., ROCKSTROM, J., OHMAN, M. C., SHYAMSUNDAR, P., STEFFEN, W., GLASER, G., KANIE, N. & NOBLE, I. 2013. Policy: Sustainable development goals for people and planet. *Nature,* 495**,** 305-7.

GUINÉE, J. 2016a. Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? *In:* CLIFT, R. & DRUCKMAN, A. (eds.) *Taking Stock of Industrial Ecology.* Cham: Springer International Publishing.

GUINÉE, J. 2016b. *Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? in Taking Stock of Industrial Ecology, S. 45-68,* Heidelberg, New York, Dordrecht, London, Springer Verlag.

HABERL, H., STEINBERGER, J. K., PLUTZAR, C., ERB, K.-H., GAUBE, V., GINGRICH, S. & KRAUSMANN, F. 2012. Natural and socioeconomic determinants of the embodied human appropriation of net primary production and its relation to other resource use indicators. *Ecological Indicators,* 23**,** 222-231.

HABERL, H., WIEDENHOFER, D., ERB, K.-H., GÖRG, C. & KRAUSMANN, F. 2017. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability,* 9**,** 1049.

HALOG, A. & MANIK, Y. 2011. Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment. *Sustainability.*

HARVEY, D. & BRAUN, B. 1996. *Justice, nature and the geography of difference*, Blackwell Oxford.

HAUFF, M. V. & JÖRG, A. 2013. *Nachhaltiges Wachstum,* München, Oldenbourg Verlag.

HAUSKNOST, D., SCHRIEFL, E., LAUK, C. & KALT, G. 2017. A Transition to Which Bioeconomy? An Exploration of Diverging Techno-Political Choices. *Sustainability,* 9**,** 669.

HECTOR, D., CHRISTENSEN, C. & PETRIE, J. 2014. *Sustainability and Sustainable Development: Philosophical Distinctions and Practical Implications*.

HOLMBERG, J., ENVIRONMENT, I. I. F. & DEVELOPMENT 1992. *Policies for a Small Planet: From the International Institute for Environment and Development,* Earthscan.

HOPWOOD, B., MELLOR, M. & O'BRIEN, G. 2005. Sustainable development: mapping different approaches. *Sustainable Development,* 13**,** 38-52.

HUMMEL, D., JAHN, T., KEIL, F., LIEHR, S. & STIEß, I. 2017. Social Ecology as Critical, Transdisciplinary Science—Conceptualizing, Analyzing and Shaping Societal Relations to Nature. *Sustainability,* 9**,** 1050.

INGRAO, C., BACENETTI, J., BEZAMA, A., BLOK, V., GOGLIO, P., KOUKIOS, E. G., LINDNER, M., NEMECEK, T., SIRACUSA, V., ZABANIOTOU, A. & HUISINGH, D. 2018. The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: Findings from this virtual special issue. *Journal of Cleaner Production,* 204**,** 471-488.

ISO 14040 2006. Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). International Organization for Standardization.

ISO 14044 2006. Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization.

JACKSON, T. 2017. *Prosperity without growth: foundations for the economy of tomorrow,* London, Routledge.

JAHN, T., BERGMANN, M. & KEIL, F. 2012. Transdisciplinarity: Between mainstreaming and marginalization. *Ecological Economics,* 79**,** 1-10.

JAROSCH, L., ZEUG, W., BEZAMA, A., FINKBEINER, M. & THRÄN, D. 2020. A Regional Socio-Economic Life Cycle Assessment of a Bioeconomy Value Chain. *Sustainability,* 12.

JORDAN, A. 2008. The governance of sustainable development: taking stock and looking forwards. *Environment and Planning C-Government and Policy,* 26**,** 17-33.

JRC, J. R. C. 2019. *European Platform on Life Cycle Assessment* [Online]. Available: https://eplca.jrc.ec.europa.eu/ [Accessed 01/12/2019 2019].

KARABARBOUNIS, L. & NEIMAN, B. 2013. The Global Decline of the Labor Share. *National Bureau of Economic Research Working Paper Series,* No. 19136.

KATES, R. W., CLARK, W. C., CORELL, R., HALL, J. M., JAEGER, C. C., LOWE, I., MCCARTHY, J. J., SCHELLNHUBER, H. J., BOLIN, B., DICKSON, N. M., FAUCHEUX, S., GALLOPIN, G. C., GRUBLER, A., HUNTLEY, B., JAGER, J., JODHA, N. S., KASPERSON, R. E., MABOGUNJE, A., MATSON, P., MOONEY, H., MOORE, B., 3RD, O'RIORDAN, T. & SVEDLIN, U. 2001. Environment and development. Sustainability science. *Science,* 292**,** 641-2.

KELLER, H., RETTENMAIER, N. & REINHARDT, G. A. 2015. Integrated life cycle sustainability assessment – A practical approach applied to biorefineries. *Applied Energy,* 154**,** 1072-1081.

KLEIN, J. T. 2008. Evaluation of interdisciplinary and transdisciplinary research: a literature review. *Am J Prev Med,* 35**,** S116-23.

KLEINSCHMIT, D., ARTS, B., GIURCA, A., MUSTALAHTI, I., SERGENT, A. & PULZL, H. 2017. Environmental concerns in political bioeconomy discourses. *International Forestry Review,* 19**,** 41-55.

KLÖPFFER, W. 2008. Life cycle Sustainability assessment of products. *International Journal of Life Cycle Assessment,* 13**,** 89-94.

KNIERIM, A., LASCHEWSKI, L. & BOYARINTSEVA, O. 2018. Inter- and Transdisciplinarity in Bioeconomy. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.

KRAMM, J., PICHLER, M., SCHAFFARTZIK, A. & ZIMMERMANN, M. 2017. Societal Relations to Nature in Times of Crisis—Social Ecology's Contributions to Interdisciplinary Sustainability Studies. *Sustainability,* 9**,** 1042.

KUBISZEWSKI, I., COSTANZA, R., FRANCO, C., LAWN, P., TALBERTH, J., JACKSON, T. & AYLMER, C. 2013. Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics,* 93**,** 57-68.

KUHMONEN, T. & KUHMONEN, I. 2015. Rural futures in developed economies: The case of Finland. *Technological Forecasting and Social Change,* 101**,** 366-374.

LAMONT, M., MALLARD, G. & GUETZKOW, J. 2006. Beyond blind faith: overcoming the obstacles to interdisciplinary evaluation. *Research Evaluation,* 15**,** 43-55.

LEWANDOWSKI, I., GAUDET, N., LASK, J., MAIER, J., TCHOUGA, B. & VARGAS-CARPINTERO, R. 2018. Context. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.

LINDQVIST, A., BROBERG, S., TUFVESSON, L., KHALIL, S. & PRADE, T. 2019. Bio-Based Production Systems: Why Environmental Assessment Needs to Include Supporting Systems. *Sustainability,* 11**,** 4678.

LIOBIKIENE, G., BALEZENTIS, T., STREIMIKIENE, D. & CHEN, X. L. 2019. Evaluation of bioeconomy in the context of strong sustainability. *Sustainable Development,* 27**,** 955-964.

LIU, J., MOONEY, H., HULL, V., DAVIS, S. J., GASKELL, J., HERTEL, T., LUBCHENCO, J., SETO, K. C., GLEICK, P., KREMEN, C. & LI, S. 2015. Systems integration for global sustainability. *Science,* 347**,** 1258832.

LUBCHENCO, J., BARNER, A. K., CERNY-CHIPMAN, E. B. & REIMER, J. N. 2015. Sustainability rooted in science. *Nature Geoscience,* 8**,** 741.

MAHBUB, N., OYEDUN, A. O., ZHANG, H., KUMAR, A. & POGANIETZ, W. R. 2019. A life cycle sustainability assessment (LCSA) of oxymethylene ether as a diesel additive produced from forest biomass. *International Journal of Life Cycle Assessment,* 24**,** 881-899.

MAŁYSKA, A. & JACOBI, J. 2018. Plant breeding as the cornerstone of a sustainable bioeconomy. *New Biotechnology,* 40**,** 129-132.

MEADOWCROFT, J. 2007. Who is in Charge here? Governance for Sustainable Development in a Complex World*. *Journal of Environmental Policy & Planning,* 9**,** 299-314.

MEBRATU, D. 1996. Sustainability as a scientific paradigm. *Lund: International Institute for Industrial Environmental Economics*.

MEBRATU, D. 1998. Sustainability and sustainable development: Historical and conceptual review. *Environmental Impact Assessment Review,* 18**,** 493-520.

MENTON, M., LARREA, C., LATORRE, S., MARTINEZ-ALIER, J., PECK, M., TEMPER, L. & WALTER, M. 2020. Environmental justice and the SDGs: from synergies to gaps and contradictions. *Sustainability Science*.

MEYER, R. 2017. Bioeconomy Strategies: Contexts, Visions, Guiding Implementation Principles and Resulting Debates. *Sustainability,* 9**,** 1031.

MICHEL, P. & ROTILLON, G. 1995. Disutility of pollution and endogenous growth. *Environmental and Resource Economics,* 6**,** 279-300.

MUSTALAHTI, I. 2018. The responsive bioeconomy: The need for inclusion of citizens and environmental capability in the forest based bioeconomy. *Journal of Cleaner Production,* 172**,** 3781-3790.

NERINI, F., SOVACOOL, B., HUGHES, N., COZZI, L., COSGRAVE, E., HOWELLS, M., TAVONI, M., TOMEI, J., ZERRIFFI, H. & MILLIGAN, B. 2019. Connecting climate action with other Sustainable Development Goals. *Nature Sustainability,* 2**,** 674-680.

NETWORK, G. F. 2019. *Global Footprint Network Glossary* [Online]. Available: https://www.footprintnetwork.org/resources/glossary/ [Accessed 27/11/2019 2019].

NIEDER-HEITMANN, M., HAIGH, K. F. & GÖRGENS, J. F. 2019. Life cycle assessment and multi-criteria analysis of sugarcane biorefinery scenarios: Finding a sustainable solution for the South African sugar industry. *Journal of Cleaner Production,* 239**,** 118039.

NILSSON, M. & COSTANZA, R. 2015. Overall Framework for the Sustainable Development Goals. *Review of Targets for the Sustainable Development Goals: The Science Perspective.* Paris: International Council for Science (ICSU).

NILSSON, M., GRIGGS, D. & VISBECK, M. 2016. Policy: Map the interactions between Sustainable Development Goals. *Nature,* 534**,** 320-322.
NITZSCHE, R., BUDZINSKI, M. & GRÖNGRÖFT, A. 2016. Techno-economic assessment of a wood-based biorefinery concept for the production of polymer-grade ethylene, organosolv lignin and fuel. *Bioresource Technology,* 200**,** 928-939.
NORSTRÖM, A. V. 2013. Social change vital to sustainability goals. *Nature,* 498**,** 299.
O'KEEFFE, S., FRANKO, U., OEHMICHEN, K., DANIEL-GROMKE, J. & THRÄN, D. 2019. Give them credit-the greenhouse gas performance of regional biogas systems. *GCB Bioenergy,* 11**,** 791-808.
O'KEEFFE, S., MAJER, S., BEZAMA, A. & THRÄN, D. 2016. When considering no man is an island—assessing bioenergy systems in a regional and LCA context: a review. *The International Journal of Life Cycle Assessment,* 21**,** 885-902.
O'NEILL, D., FANNING, A., STEINBERGER, J., LAMB, W., TREBECK, K. & RAWORTH, K. 2019. *A Good Life For All Within Planetary Boundaries* [Online]. Leeds: University of Leeds. Available: https://goodlife.leeds.ac.uk/about/ [Accessed 27/11/2019 2019].
O'NEILL, D. W., FANNING, A. L., LAMB, W. F. & STEINBERGER, J. K. 2018. A good life for all within planetary boundaries. *Nature Sustainability,* 1**,** 88-95.
OECD 2018. *Meeting Policy Challenges for a Sustainable Bioeconomy*.
OLSSON, O., BRUCE, L., HEKTOR, B., ROOS, A., GUISSON, R., LAMERS, P., HARTLEY, D., PONITKA, J., HILDEBRAND, D. & THRÄN, D. 2016. Cascading of woody biomass: definitions, policies and effects on international trade. IEA Bioenergy.
ONAT, N. C., KUCUKVAR, M., HALOG, A. & CLOUTIER, S. 2017. Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives. *Sustainability,* 9**,** 706.
OPHER, T., FRIEDLER, E. & SHAPIRA, A. 2019. Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. *The International Journal of Life Cycle Assessment,* 24**,** 1319-1332.
PANOUTSOU, C., MANFREDI, S. & KAVALOV, B. 2013. Biomass resource efficiency for the biobased industries. Ispra: Joint Research Centre (JRC).
PARRIQUE T., B. J., BRIENS F., C. KERSCHNER, KRAUS-POLK A., KUOKKANEN A., SPANGENBERG J.H. 2019. Decoupling Debunked - Evidence and arguments against green growth as a sole strategy for sustainability. Brussels: The European Environmental Bureau.
PELTOMAA, J. 2018. Drumming the Barrels of Hope? Bioeconomy Narratives in the Media. *Sustainability,* 10**,** 4278.
PFAU, S. F., HAGENS, J. E., DANKBAAR, B. & SMITS, A. J. M. 2014. Visions of Sustainability in Bioeconomy Research. *Sustainability,* 6**,** 1222-1249.
PICHLER, M., SCHAFFARTZIK, A., HABERL, H. & GÖRG, C. 2017. Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. *Current Opinion in Environmental Sustainability,* 26-27**,** 32-36.
PURVIS, B., MAO, Y. & ROBINSON, D. 2019. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science,* 14**,** 681-695.
PYKA, A. & PRETTNER, K. 2018. Economic Growth, Development, and Innovation: The Transformation Towards a Knowledge-Based Bioeconomy. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.
RAMCILOVIC-SUOMINEN, S. & PÜLZL, H. 2018. Sustainable development – A 'selling point' of the emerging EU bioeconomy policy framework? *Journal of Cleaner Production,* 172**,** 4170-4180.
RAMETSTEINER, E., PÜLZL, H., ALKAN-OLSSON, J. & FREDERIKSEN, P. 2011. Sustainability indicator development—Science or political negotiation? *Ecological Indicators,* 11**,** 61-70.
REDCLIFT, M. R. & BENTON, T. 1994. *Social Theory and the Global Environment,* Routledge.
RHYNER, J. 2016. *In:* EARTH, F. (ed.) *The contribution of science in implementing the Sustainable Development Goals.* Stuttgart: German Committee Future Earth.
ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN III, F. S., LAMBIN, E. F., LENTON, T. M., SCHEFFER, M., FOLKE, C., SCHELLNHUBER, H. J., NYKVIST, B., DE WIT, C. A., HUGHES, T., VAN DER LEEUW, S., RODHE, H., SÖRLIN, S., SNYDER, P. K., COSTANZA, R., SVEDIN, U., FALKENMARK, M., KARLBERG, L., CORELL, R. W.,

FABRY, V. J., HANSEN, J., WALKER, B., LIVERMAN, D., RICHARDSON, K., CRUTZEN, P. & FOLEY, J. A. 2009. A safe operating space for humanity. *Nature*, 461**,** 472.

ROCKSTRÖM, J. & SUKHDEV, P. 2016. *How food connects all the SDGs* [Online]. Stockholm Resilience Centre. Available: http://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html [Accessed 01. November 2017].

RONZON, T. & M'BAREK, R. 2018. Socioeconomic Indicators to Monitor the EU's Bioeconomy in Transition. *Sustainability,* 10**,** 1745.

ROSENFIELD, P. L. 1992. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. *Social Science & Medicine,* 35**,** 1343-1357.

SCHAEFER, F., LUKSCH, U., STEINBACH, N., CABEÇA, J. & HANAUER, J. 2006. Ecological Footprint and Biocapacity - The world's ability to regenerate resources and absorb waste in a limited time period. Luxembourg: European Commission.

SCHAUBROECK, T. 2018. Towards a general sustainability assessment of human/industrial and nature-based solutions. *Sustainability Science,* 13**,** 1185-1191.

SCHAUBROECK, T. & RUGANI, B. 2017. A Revision of What Life Cycle Sustainability Assessment Should Entail: Towards Modeling the Net Impact on Human Well-Being. *Journal of Industrial Ecology,* 21**,** 1464-1477.

SCHLEYER, C., LUX, A., MEHRING, M. & GÖRG, C. 2017. Ecosystem Services as a Boundary Concept: Arguments from Social Ecology. *Sustainability,* 9**,** 1107.

SCHMIDT-TRAUB, G., KROLL, C., TEKSOZ, K., DURAND-DELACRE, D. & SACHS, J. D. 2017. National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. *Nature Geoscience,* 10**,** 547.

SCHUBERT, D. K. J., THUß, S. & MÖST, D. 2015. Does political and social feasibility matter in energy scenarios? *Energy Research & Social Science,* 7**,** 43-54.

SCHÜTTE, G. 2018. What kind of innovation policy does the bioeconomy need? *New Biotechnology,* 40**,** 82-86.

SHEPHERD, K., HUBBARD, D., FENTON, N., CLAXTON, K., LUEDELING, E. & DE LEEUW, J. 2015. Policy: Development goals should enable decision-making. *Nature,* 523**,** 152-4.

SIEBERT, A., BEZAMA, A., O'KEEFFE, S. & THRÄN, D. 2016. Social life cycle assessment: in pursuit of a framework for assessing wood-based products from bioeconomy regions in Germany. *The International Journal of Life Cycle Assessment,* 23**,** 651-662.

SIEBERT, A., O'KEEFFE, S., BEZAMA, A., ZEUG, W. & THRÄN, D. 2018. How not to compare apples and oranges: Generate context-specific performance reference points for a social life cycle assessment model. *Journal of Cleaner Production,* 198**,** 587-600.

SMETANA, S., TAMÁSY, C., MATHYS, A. & HEINZ, V. 2017. *Sustainability Assessment of Agribusiness Clusters: A Case Study Based on Regional Sustainability Assessment Methodology*.

SMULDERS, S. 1995. Entropy, environment, and endogenous economic growth. *International Tax and Public Finance,* 2**,** 319-340.

SOEB.DE, P. S. R. 2020. *What does "socioeconomic" mean?* [Online]. Göttingen: Soziologisches Forschungsinstitut Göttingen (SOFI) e.V. an der Georg-August-Universität. Available: http://www.soeb.de/en/overview/meaning-of-socioeconomic/ [Accessed 10.06.2020 2020].

SPAISER, V., RANGANATHAN, S., SWAIN, R. B. & SUMPTER, D. J. T. 2017. The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. *International Journal of Sustainable Development & World Ecology,* 24**,** 457-470.

STAFFAS, L., GUSTAVSSON, M. & MCCORMICK, K. 2013. Strategies and Policies for the Bioeconomy and Bio-Based Economy: An Analysis of Official National Approaches. *Sustainability,* 5**,** 2751-2769.

STEFFEN, W., ROCKSTROM, J., RICHARDSON, K., LENTON, T. M., FOLKE, C., LIVERMAN, D., SUMMERHAYES, C. P., BARNOSKY, A. D., CORNELL, S. E., CRUCIFIX, M., DONGES, J. F., FETZER, I., LADE, S. J., SCHEFFER, M., WINKELMANN, R. & SCHELLNHUBER, H. J. 2018. Trajectories of the Earth System in the Anthropocene. *Proc Natl Acad Sci U S A,* 115**,** 8252-8259.

STERN, T., PLOLL, U., SPIES, R., SCHWARZBAUER, P., HESSER, F. & RANACHER, L. 2018. Understanding Perceptions of the Bioeconomy in Austria—An Explorative Case Study. *Sustainability,* 10**,** 4142.

SUWELACK, K. 2016. *Conversion Technology and Life Cycle Assessment of Renewable Resources*, Hohenheim, Hohenheim University.

TAKALA, T., TIKKANEN, J., HAAPALA, A., PITKÄNEN, S., TORSSONEN, P., VALKEAVIRTA, R. & PÖYKKÖ, T. 2019. Shaping the concept of bioeconomy in participatory projects – An example from the post-graduate education in Finland. *Journal of Cleaner Production*, 221**,** 176-188.

TAYLOR, P. G., ABDALLA, K., QUADRELLI, R. & VERA, I. 2017. Better energy indicators for sustainable development. *Nature Energy*, 2**,** 17117.

THRÄN, D., BEZAMA, A., PINKWART, A., BUDZINSKI, M., GAWEL, E., GRÖNGRÖFT, A., HAGEDORN, A., HAGEMANN, N., HAUSLADEN, I., HILDEBRANDT, J., HILLEBRAND, K., HOEFT, M., KIRCHGEORG, M., KÖCK, W., LICHTENBERG, A., MAJER, S., MOESENFECHTEL, U., MÜLLER-LANGER, F., NITZSCHE, R., PANNICKE, N., RUDOLPH, K., SIEBERT, A. & TRONICKE, C. 2014. Hintergrundpapier zum Themengebiet 5 „Management der Bioökonomie" Verbundprojekt 5.1 „Begleitforschung". Leipzig: Deutsches Biomasse Forschungszentrum, Helmholtz-Zentrum für Umweltforschung Leipzig, Handelshochschule Leipzg.

TISDELL, C. A. 2015. *Sustaining biodiversity and ecosystem functions: economic issues*, Edward Elgar Publishing.

TRAVERSO, M., FINKBEINER, M., JØRGENSEN, A. & SCHNEIDER, L. 2012. Life Cycle Sustainability Dashboard. *Journal of Industrial Ecology*, 16**,** 680-688.

TRZYNA, T. C., OSBORN, J. K., NATURE, I. U. F. C. O. & RESOURCES, N. 1995. *A sustainable world: defining and measuring sustainable development*, Published for IUCN - the World Conservation Union by the International Center for the Environment and Public Policy, California Institute of Public Affairs.

UN, U. N. 2019a. Global Sustainable Development Report.

UN, U. N. 2019b. The Sustainable Development Goals Report. New York.

UNEP, U. N. E. P. 2009. *Guidelines for Social Life Cycle Assessment of Products*, Paris, United Nations Environment Programme, DTIE.

UNEP, U. N. E. P. 2011. *Towards a Life Cycle Sustainability Assessment - Making informed choices on products*, UNEP/SETAC Life Cycle Initiative.

VAN RENSSEN, S. 2014. A bioeconomy to fight climate change. *Nature Climate Change*, 4**,** 951.

VERDIER, T. Environmental Pollution and Endogenous Growth. 1995 Boston, MA. Birkhäuser Boston, 175-200.

VICTOR, T. Y. H., CHANG, P. & BLACKBURN, K. 1994. Endogenous Growth, Environment and R&D. *In:* CARRARO, C. (ed.) *Trade, Innovation, Environment.* Dordrecht: Springer Netherlands.

VOGT GWERDER, Y., MARQUES, P., DIAS, L. C. & FREIRE, F. 2019. Life beyond the grid: A Life-Cycle Sustainability Assessment of household energy needs. *Applied Energy*, 255**,** 113881.

WAGNER, M. & LEWANDOWSKI, I. 2018. Markets, Sustainability Management and Entrepreneurship - Life-Cycle Sustainability Assessment. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.

WARD, J. D., SUTTON, P. C., WERNER, A. D., COSTANZA, R., MOHR, S. H. & SIMMONS, C. T. 2016. Is Decoupling GDP Growth from Environmental Impact Possible? *PLOS ONE*, 11**,** e0164733.

WESSELER, J. & VON BRAUN, J. 2017. Measuring the Bioeconomy: Economics and Policies. *Annual Review of Resource Economics, Vol 9*, 9**,** 275-298.

WILLIAMS, J. 2010. *UN: Development is possible without growth* [Online]. https://earthbound.report. Available: https://earthbound.report/2010/11/08/un-development-is-possible-without-growth/ [Accessed 2019].

WULF, C., WERKER, J., BALL, C., ZAPP, P. & KUCKSHINRICHS, W. 2019. Review of Sustainability Assessment Approaches Based on Life Cycles. *Sustainability*, 11**,** 5717.

ZAMAGNI, A. 2012. Life cycle sustainability assessment. *International Journal of Life Cycle Assessment*, 17**,** 373-376.

ZAMAGNI, A., PESONEN, H.-L. & SWARR, T. 2013. From LCA to Life Cycle Sustainability Assessment: concept, practice and future directions. *The International Journal of Life Cycle Assessment.*

ZEUG, W., BEZAMA, A., MOESENFECHTEL, U., JÄHKEL, A. & THRÄN, D. 2019. Stakeholders' Interests and Perceptions of Bioeconomy Monitoring Using a Sustainable Development Goal Framework. *Sustainability,* 11**,** 1511.

ZIMEK, M., SCHOBER, A., MAIR, C., BAUMGARTNER, R. J., STERN, T. & FÜLLSACK, M. 2019. The Third Wave of LCA as the "Decade of Consolidation". *Sustainability,* 11**,** 3283.

ZÖRB, C., LEWANDOWSKI, I., KINDERVATER, R., GÖTTERT, U. & PATZELT, D. 2018. Biobased Resources and Value Chains. *In:* LEWANDOWSKI, I. (ed.) *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy.* Cham: Springer International Publishing.

Appendix A

Table A1, SDG Sub-Goals and their relevances allocated to the human needs, provisioning system and planetary boundaries. Since the SDG subgoals are only to be understood in the SRN, this assignment is not distinct. The relevance factor (R) is used in a HILCSA as a weighting factor for the corresponding indicators.

Human Needs			Provisioning System			Planetary Boundaries		
SDG Code	SDG Sub-Goal	R	SDG Code	SDG Sub-Goal	R	SDG Code	SDG Sub-Goal	R
1.1	Eliminate extreme poverty, pay equity	6.94	6.1	Access to affordable drinking water, food security	8.61	13.1	Emergency plans	4.17
1.2	Poverty reduction, pay equity	6.94	6.2	Sanitation / hygiene	4.44	13.2	Climate protection measures, politics, strategies, planning	8.89
1.4	Enable economic participation for all people	6.94	6.3	Increase water quality, pollution / chemicals, sewage / reprocessing	8.33	13.3	Education and awareness about climate protection	4.44
1.5	Increase resistance of population against extreme climate events	6.11	6.4	Efficient water use of all sectors	7.22	13.a	Financing of climate protection measures in developing countries	6.94
1.a	Financial support / development aid, eradication of poverty	5.56	6.5	Integrated management of water resources	5.56	13.b	Development of management capacities, climate protection measures	6.94
2.1	Food access, food security	8.89	6.6	Protection of all water-related ecosystems	8.89	14.1	Reduce marine pollution, marine litter / nutrient pollution	8.33
2.2	End malnutrition, food security	8.61	6.a	Capacity building for wastewater treatment / reprocessing	4.17	14.2	Sustainable management of coastal ecosystems	5.83
2.3	Increase agricultural productivity, income (small producers)	6.39	6.b	Improvement of water management, sanitation	5.56	14.3	Reduce acidification of the oceans	6.94
2.4	Sustainable systems in food production (resilience)	8.61	7.1	Access affordable, modern energy services	6.94	14.4	Overfishing / management plans	8.33

2.5	Preserve genetic diversity of seeds / plants / animals	8.33	7.2	Increase share of renewable energies, energy mix	5.56	14.5	Preserve coastal and marine areas	8.33
2.a	Investment in rural infrastructure, agricultural research and consulting	8.61	7.3	Double rate of increase of energy efficiency	5.83	14.6	Prohibit fishing subsidies	5.56
2.b	Trade restrictions, - prevent distortions, stop agricultural export subsidies	4.44	7.a	Access to research and technology, renewable energy	6.94	14.7	Sustainable management of fisheries, aquaculture, tourism	8.33
2.c	Stability food market, fluctuations of food prices, reserves	8.33	7.b	Infrastructure development, modern energy services	6.94	14.a	Scientific cooperation, transfer of marine technologies / research capacities	6.94
3.9	Reduce pollution of air/water/ soil, health protection	8.61	8.2	Econ. productivity increase through diversification	3.33	14.c	Access small-scale marine resources / markets	6.94
4.1	Equal access / free education from elementary schools on (girls / boys)	3.33	8.3	Promoting decent work, innovation, creativity, SMEs	8.61	14.b	Conservation / sustainable use of oceans, convention on the law of the sea	4.17
4.2	Equal access / free education from preschool / kindergarten on (girls / boys)	3.33	8.4	Resource efficiency in consumption / production	5.83	15.1	Preservation / sustainable use of terrestrial and inland freshwater ecosystems	7.50
4.3	Promote gender equality	6.11	8.5	Productive full employment, decent work, pay equity	3.06	15.2	Sustainable forest management / reforestation	8.61
4.5	Gender disparities (parity indices)	5.56	8.6	Increase share of youth employment, education and vocational training	4.72	15.3	Combat desertification, area remediation	6.94
4.7	Education for sustainable development	8.61	8.8	Worker rights, labor protection rights, promoting safe work environment	0.00	15.4	Conserving mountain ecosystems / biodiversity	7.50
4.b	Increase number of scholarships	4.17	8.7	Worker rights, abolition of forced	5.00	15.5	Protecting natural habitats, threatened	8.33

				labor / trafficking / child labor			species, biodiversity	
5.1	Eliminate discrimination against women	5.83	8.10	Promote national financial institutions for financial infrastructure	6.94	15.6	Just use / access to benefits of genetic resources	6.94
5.a	Financial equality, legal framework for women (e.g. pension, real estate)	3.89	8.a	Support developing countries / technical assistance	5.83	15.7	Combat poaching / trade of protected plants	4.17
11.2	Infrastructure / traffic system	4.44	9.1	Resilient infrastructure	5.56	15.8	Prevent invasive species	7.22
11.3	Sustainable urbanization	7.50	9.2	Sustainable industrialization	5.83	15.9	Aichi biodiversity targets, ecosystem and biodiversity values	8.89
11.4	Protection of world cultural and natural heritage	5.56	9.3	Access financial services SMEs	6.94	15.a	Conservation, sustainable use, biodiversity, ecosystems	8.61
11.6	Reduce urban environmental impacts, air quality, waste treatment	9.17	9.4	Sustainable renewal of industrial infrastructures	8.33	15.b	Forest conservation / reforestation	8.61
11.a	Regional development planning, linkage of urban and rural areas	7.78	9.5	Strengthen / promote scientific research in developing countries	5.83	15.c	Combating poaching / wildlife trade	3.89
11.b	Urban planning of resource efficiency / mitigation of climate change	6.94	9.b	Support local technology development in developing countries	5.56			
11.c	Support sustainable construction, local materials)	7.22	9.c	Access to information and communication technology	5.83			
			10.1	Income growth	5.83			
			10.5	Regulation / supervision of global financial markets	3.33			
			10.6	Improvement of representation / participation of	7.50			

	developing countries	
10.a	Justice, treatment of developing countries	4.72
10.b	Efficient and effective development assistance / financial flows / direct investment	7.22
12.1	Sustainable consumption and production patterns	7.50
12.2	Sustainable management of natural resources	8.89
12.3	Food waste / losses, post-harvest losses, resource efficiency	8.61
12.4	Environmentally friendly handling of chemicals and waste	8.61
12.5	Reduction of waste generation (prevention, reduction, recycling and reuse)	9.17
12.6	Reporting on sustainability information	8.61
12.7	Sustainable public procurement	5.28
12.8	Information for consciousness about sustainable development	8.33
12.a	Strengthen research on sustainable production / consumption	8.89

12.b	Monitoring sustainable tourism	5.56
12.c	Abolish fossil fuel subsidies	5.83
16.5	Reduction of bribery / corruption	7.22
16.7	Democratic decision-making	5.56
17.1	Mobilizing local resources, taxes and duties	8.33
17.2	Compliance pledges financial assistance	6.94
17.3	Financial and technical cooperation	6.94
17.4	Reduction of over-indebtedness / external debt	8.89
17.6	North-south / south-south / triangular cooperation	8.33
17.7	Diffusion of environmentally sound technologies	6.94
17.11	Increase exports of developing countries	5.56
17.13	Global macroeconomic stability	7.22
17.14	Policy coherence in sustainable development	5.56
17.15	Political scope regarding poverty elimination	4.44
17.18	Capacity expansion in data collection	8.33
17.19	Measurement of sustainable development	4.17